BIG ROCK NUCLEAR POWER PLANT
HYDROLOGICAL SURVEY

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I. INTRODUCTION

This report summarizes the results of studies carried on during the summer of 1960 in Little Traverse Bay of Lake Michigan. The studies, supported by Consumers Power Company, were designed to obtain a variety of data relevant to the assessment of hazards associated with the operation of a nuclear reactor power-generation facility at Big Rock Point at the south side of the mouth of Little Traverse Bay.

Several persons of the Great Lakes Research Division of The University of Michigan's Institute of Science and Technology have participated in the gathering and processing of the data and in the preparation of this report. Their names, and the sections of the report for which they were primarily responsible, are:

Vincent E. Noble, Associate Research Physicist, Section VI;
Charles F. Powers, Associate Research Oceanographer, Sections IV, V;
William E. French, Assistant Research Geologist, Section III;
John C. Ayers, Research Oceanographer, Sections I, II, VII, VIII, IX, and X.

Dr. Ayers also served as over-all director of the studies and as general editor of the report.

James R. Stockard and Thomas Rodeheffer, as summer assistants, contributed materially in the field phases of the studies.

Messrs. Robert D. Allen and A. L. Bethel, of Consumers Power Co., very kindly provided help in our orientation to the problem, and in furnishing technical information.

II. TOPOGRAPHY AND BATHYMETRY OF LITTLE TRAVERSE BAY

Little Traverse Bay is a triangular embayment of Lake Michigan and is situated in Charlevoix and Emmet Counties in the northwestern portion of the Lower Peninsula of Michigan. The bay is centered at approximately 45°24' north latitude and 85°00' west longitude and is about 12 miles by 10 miles in its greatest dimensions. For the purpose of this study, the mouth of the bay is taken to be along a line from Big Rock Point, in Charlevoix County, on the south shore to Seven Mile Point, in Emmet County, on the north shore.

The shoreline of the bay is relatively regular. Small points tend to occur in series which alternate with longer stretches of smooth shoreline. Two series of small points are present along the south shore; one series is situated between Big Rock Point and Nine Mile Point, the other is in the adjoined waterfront areas of Petoskey and Bayview. On the north shore another series of small points is situated about mid-way between Harbor Springs and Seven Mile Point.

The major shoreline feature of the bay is a large peninsula, Harbor Point, at Harbor Springs. This peninsula is about a mile long and about 0.4 mile in width at its base. It arises from the north shore at Harbor Springs and extends into the bay in a direction from northwest to southeast.

Along most of its perimeter the bay is surrounded by hills rising from 300 to 600 feet above the level of the bay. These hills are morainic relics of the Port Huron stage of the Wisconsin glaciation and have been subject to some modification by the later Valders glaciation which closed the Wisconsin glacial age.

The topography of the area around Little Traverse Bay is sufficiently well indicated by Fig. V-7 of Part B, Consumers Power Company Preliminary Hazards Summary Report, which will not be duplicated here.

The underwater topography, or bathymetry, of Little Traverse Bay is not presented in the Preliminary Hazards Summary Report and is presented here (Fig. 1) because of its indirect bearing upon certain of the features of the over-all water circulation in the bay.

The bathymetry of Little Traverse Bay is characterized by submerged slopes of irregular width which descend into the depths of the bay, and by a high degree of irregularity of the bottom topography. Maximum depth in the bay occurs in a small area in the bay mouth where, about two miles north of Big Rock Point, depths in excess of 300 feet are charted. About seven miles north of Big Rock Point lies an irregular north-south ridge which is extensive at 150 feet and has only 100 feet of water over its apex.

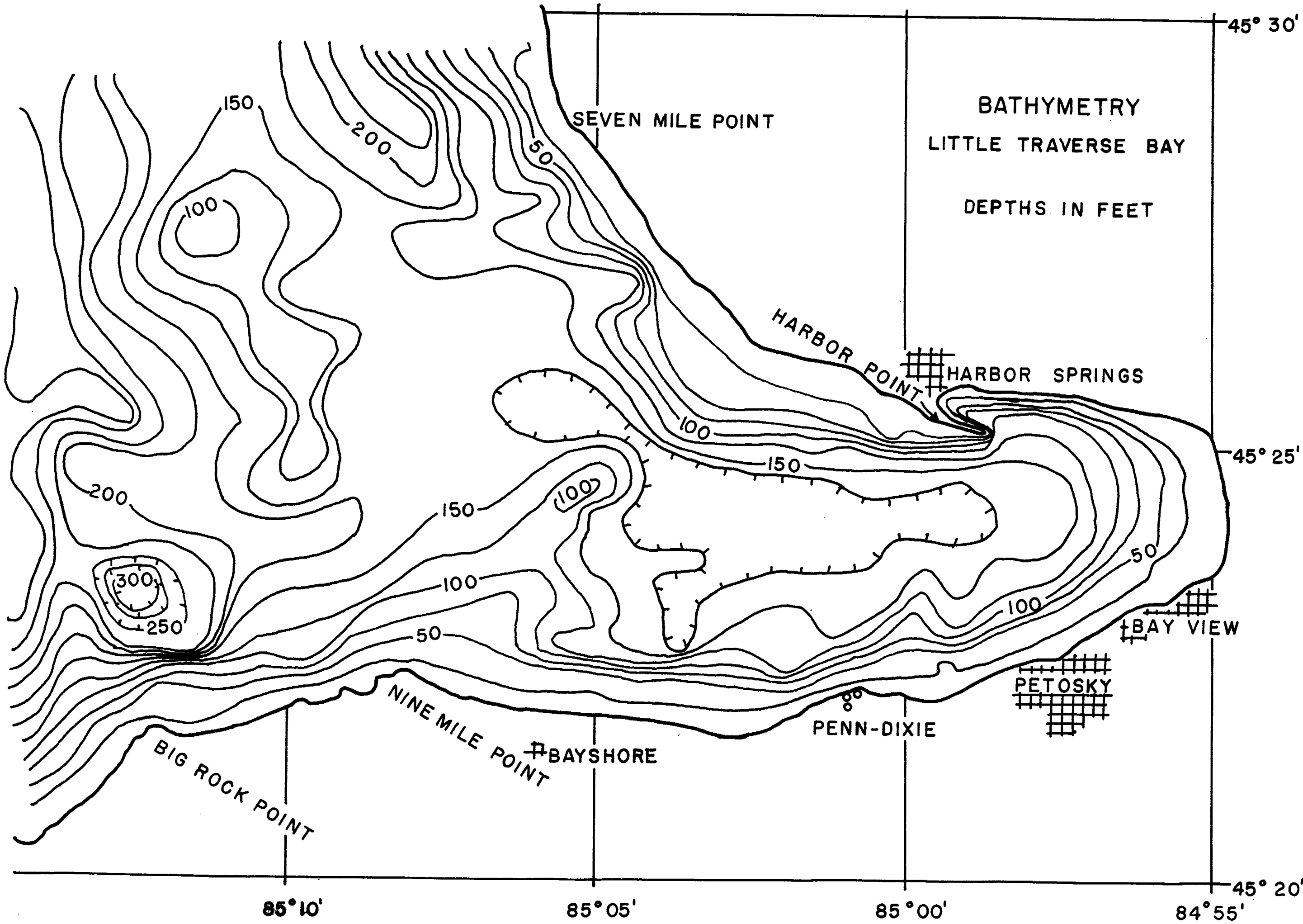

Fig. 1. Bathymetry of Little Traverse Bay.

Protruding northeastward from Nine Mile Point is a partial "sill" which at depths less than 125 feet is continuous for about two-thirds the width of the bay. Depths less than 100 feet occur in a small area at the outer end of the sill.

A relatively large portion of bay-bottom lying at depths greater than 175 feet extends along the axis of the bay from north of Bay Shore to north of Petoskey. This secondary deep portion has a large tributary-like extension reaching toward the south and its west end is severely constricted by the outer end of the sill reaching northeast from Nine Mile Point. The head of the tributary-like southward extension lies only about a mile from shore between Bay Shore and the Penn-Dixie Cement Company plant; here the bottom drops steeply from 50 feet to more than 175 feet. Similar but less pronounced trough-like landward extensions of deeper water lie about a mile north and west of the Penn-Dixie plant and about a mile north and west of Petoskey. These troughs and the large deep water "tributary" are believed to play roles in the normal westerly-wind circulation of the waters of the bay.

III. OFFSHORE GEOLOGY AT BIG ROCK POINT

As an ancillary operation to the current and dilution studies made in the vicinity of the Big Rock Point Reactor Site, a limited survey of the underwater geology was made.

The primary purpose of this survey was to investigate the feasibility of underwater geological mapping by means of SCUBA diving. However, these dives yielded a limited amount of information about the offshore geology near the plant site which may be of interest as being correlative to wells bored on the site.

The survey consisted of four traverses made at right angles to the shoreline in the area from Big Rock Point to the east side of the Reactor Site clearing and extending 2000 feet out into the lake. Each traverse was made by laying a 2000-foot length of line from the shore out along the lake bottom and inspecting the bottom by swimming along this line. The line was marked at 50-foot intervals to enable sample location. The samples and field notes were correlated with fathometer records made along each line at the time it was being laid.

The accompanying diagram (Fig. 2) shows the four sonic profiles obtained by recording fathometer and a tentative correlation along their outer ends. The main feature illustrated is the greater declivity off Big Rock Point, which indicates that the point does not continue very far offshore.

There is a well defined valley which begins between lines II and III, trends northeast across line III, and leaves the area between the outer ends of lines III and IV. The head of this valley may be correlative with the small embayment on the west edge of the Reactor Site.

The limestone outcrop on line I is clearly seen as a series of step-like drops in the bottom profile. Marked irregularities in the profile of line IV indicate the location of the glacial till outcrops. In addition, the sonic profiles indicate the presence of many boulders of about the same size as the Big Rock.

A contour map of the underwater areal topography was included with the preliminary report.

According to the literature summary by Pohl (1930), the Big Rock Point area is underlaid by rocks of the Traverse formation of Devonian age. This formation consists of a series of shaley and cherty limestones.

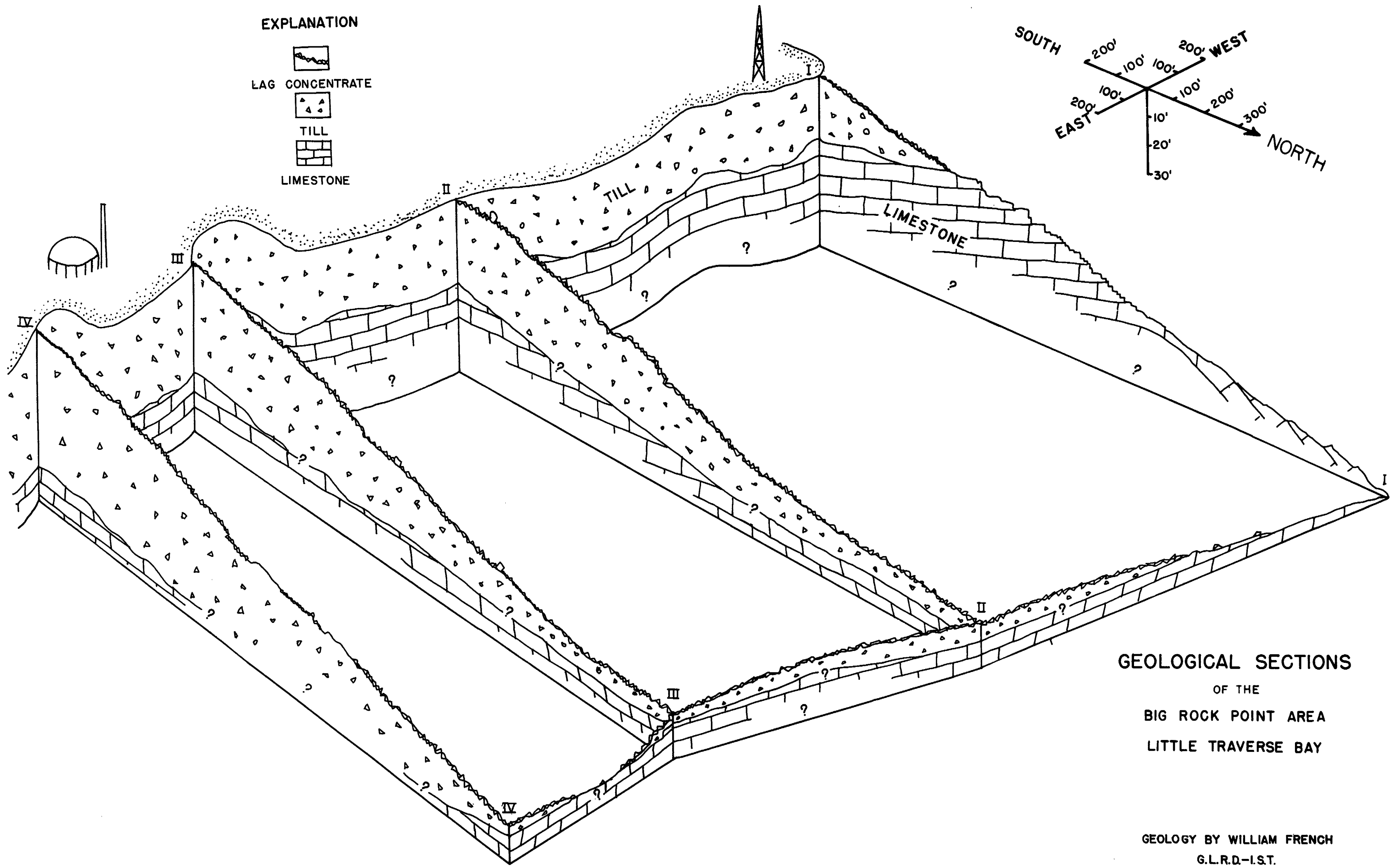

Fig. 2. Geological sections of the Big Rock Point area of Little Traverse Bay.

The bedrock found outcropping offshore is chiefly a light brown, hard limestone with a few small layers of softer grey limestone. This has been tentatively placed in either the Charlevoix stage of the Petoskey limestone or the Gravel Point stage of the Alpena limestone.

The geological section of line I depicts the limestone as undergoing a reversal of dip and tending to dip lakeward at the outer end of the line. This is inferred from topography but is supported by other evidence from the regional topography which shows that the structure of the bedrock in the region is irregular. This may be due to solution, slumpage, and recementation of the underlying strata in the past. The dips shown on the cross sections are, of course, exaggerated and are in reality only one to two degrees. The depth-to-bedrock in the outer portions of lines II, III, and IV, is inferred and is based on topographic indications, from an additional fathogram, that beyond the end of line III the bedrock outcrops at a depth of 50 feet. The depth-to-bedrock shown at the inner ends of lines III and IV is based on the test borings made at the reactor site (Zumberge, 1960).

Except for the outcrop area off Big Rock Point, the bedrock in the entire area is covered by a layer of reddish-brown glacial till. This till has been identified as belonging to the Valders stage of the Wisconsin glaciation and is typically a hard, sandy clay containing pebbles, cobbles, and boulders.

Wave erosion of the till surface has removed the clay and sand leaving the pebbles, cobbles, and boulders to form a lag concentrate. This is the source of the boulder pavement which covers the lake bottom. This surficial deposit is not very thick. Experimental excavation near the reactor area reached till about two feet below the bottom. In two places along line IV current and/or ice erosion has removed the lag concentrate cover, leaving bare till which shows scour effects indicative of at least periodic rapid bottom currents.

IV. BAY CIRCULATION UNDER PREVAILING WINDS

One objective of the field operations during the summer of 1960 was the measurement of surface currents under prevailing winds over as much of Little Traverse Bay as possible. This was to be in addition to, and subsidiary to, detailed observations of currents under various wind regimens in the immediate vicinity of the plant site. This objective was partially attained, but a cessation of winds from westerly quarters during the latter half of August precluded as complete a coverage of the bay as had been anticipated. The circulation pattern of the bay (Fig. 3) must consequently be regarded as tentative. In Fig. 4, those parts of the pattern which are uncertain are indicated by dashed arrows.

Measurements of surface currents were by "current poles" and "current drogues." Each current pole consisted of a four-foot length of fir 2 x 4, ballasted at one end with two bricks, so that it floated in a vertical position. The top six or eight inches protruded above the surface of the water, and bore a small, bright orange pennant.

Each current drogue consisted of a truncate cone of 26-gauge galvanized sheet metal, 30 inches in height, 36 inches in diameter at the large end, and 32 inches at the small end. Both ends were open, so that the structure resembled a bottomless washtub. The small end of the drogue was attached to a float consisting of a pair of gallon glass jugs bearing an orange pennant atop a bamboo flagstaff five feet long; the jugs floated in almost submerged position and exposed only a small surface area to the wind. All poles and drogues bore identifying numbers or letters. Under operating condition, poles and drogues were released in series, as many as fifteen being used during a given operation.

Although the drogues exhibited slightly less response to the direct effect of wind than did the poles, repeated comparisons indicated that the windage exhibited by the poles did not result in a velocity or path of travel significantly different from that of the drogues. Both were used throughout the entire survey, so that continual cross-checks could be made. In any series of sets, the procedure usually followed was that of alternating poles and drogues, with poles being used for all sets made in shallow water close to shore.

The point of release of pole or drogue was ascertained by sextant fix to landmarks on shore. The time of release was recorded, as well as the local wind velocity and direction. During any day's operations, poles and drogues were left in the water for a number of hours, during which period each was located by sextant fix several times. Plotting of these fixes allowed reconstruction of the paths of travel, and distance traveled in elapsed time between fixes gave a measure of speed of progress.

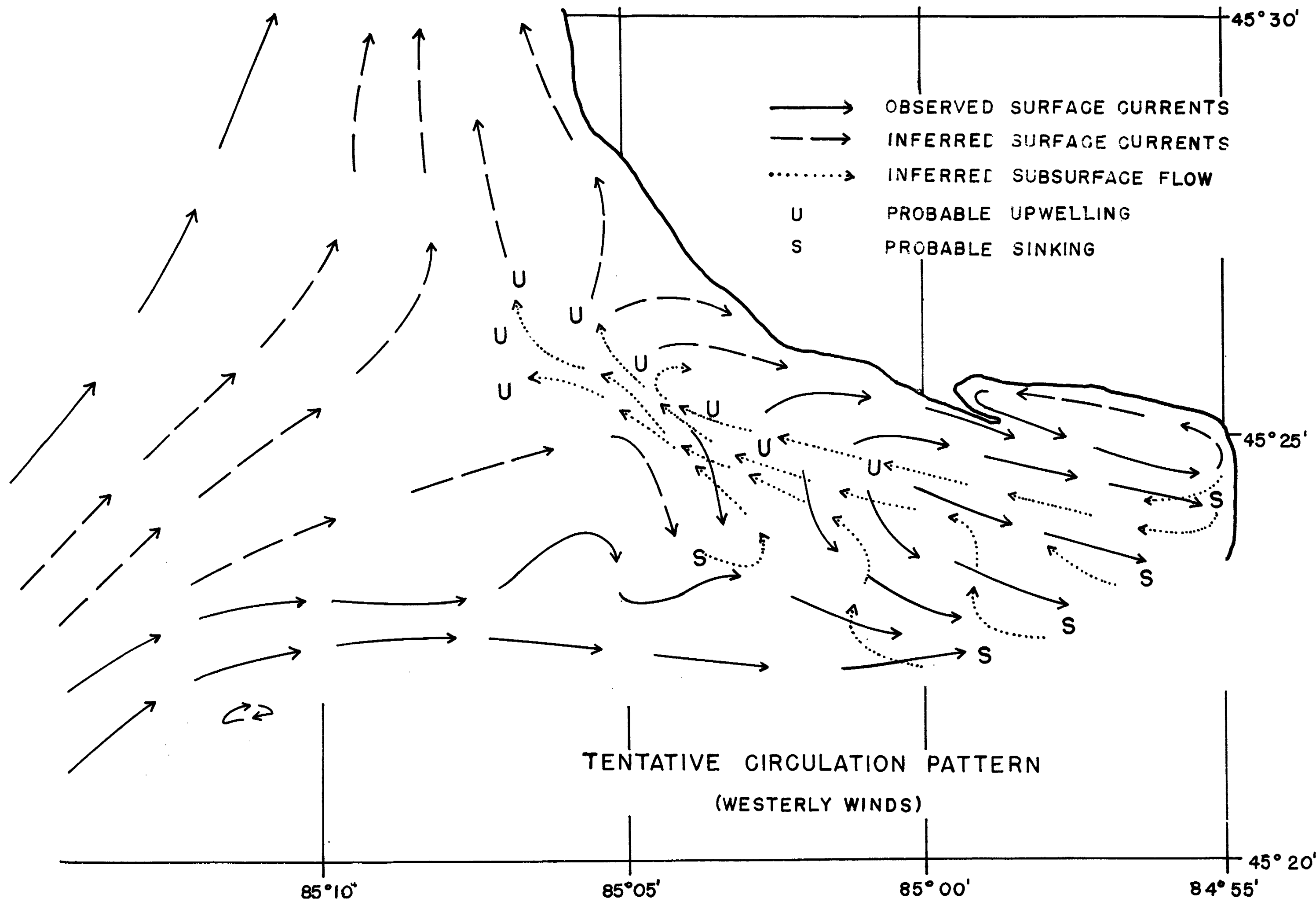

Fig. 3. Tentative circulation pattern of Little Traverse Bay under westerly winds.

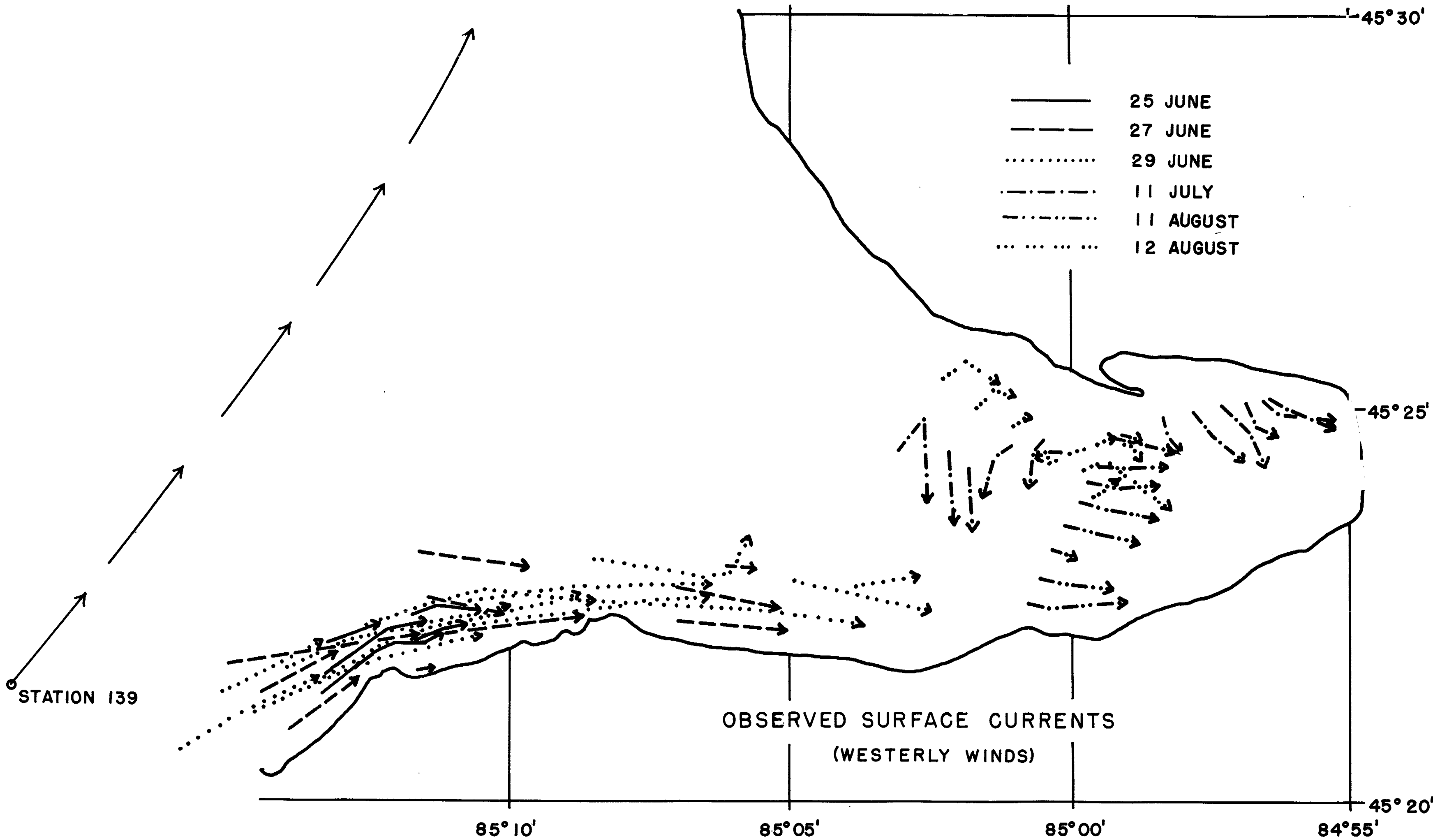

Fig. 4. Observations of surface currents made under westerly winds.

Eight sets of observations were obtained on winds essentially from a westerly direction. They are summarized in Table I and shown in Fig. 4.

TABLE I

CURRENT OBSERVATIONS UNDER WESTERLY WINDS

Date	Wind		Current		Location
	Direction From	Velocity (mph)	Direction Toward	Velocity (mph)(avg)	
25 June	W	8-12	NE	0.34	Off Big Rock Point.
27 June	SW	8-10	NE-E	0.40	Between Point McSauba and Penn-Dixie.
	W	15-20			Between Point McSauba and Penn-Dixie.
29 June	W	8-12	NE-E	0.72	Between Point McSauba and Penn-Dixie.
11 July	WSW	8-12	S	0.30	Along lat. 45°25' between Forest Beach and west end of Harbor Point.
11 July	WSW-WNW	8-12	SE	0.22	Along lat. 45°25' between east end of Harbor Point and inner end of bay.
11 Aug	W	15-20	E	0.35	Between Penn-Dixie and Harbor Point.
12 Aug	W	6-15	NE-E	0.16	1/2 mile offshore between Forest Beach and west end of Harbor Point.
12 Aug	W	6-15	NE-SE	0.35	North-central portion of bay off Harbor Point.

All drogues, poles, and dye patches released in the main south-shore current between Point McSauba and the Penn-Dixie plant moved essentially parallel to shore and toward the head of the bay. In no case was movement in the opposite direction found under westerly winds. Between Nine Mile Point and the cement plant there was some offshore movement of drogues.

Of the releases made on 11 July, those west of Harbor Point moved essentially to the south while those from the point eastward moved east or southeast toward the inner end of the bay (see Fig. 4).

On 11 August, the drogues and poles released between the cement plant and Harbor Point all moved east, toward the head of the bay.

On 12 August, the westernmost three drogues and poles (released off Forest Beach) were set closer to shore than those of 11 July; they first moved northeast toward shore, and then turned southeastward toward the tip of Harbor Point after reaching the four-fathom contour. The remaining two, set near the center of the bay south of Harbor Point, moved toward the head of the bay.

In addition to the observations described above, the movements of drift bottles released by Ayers et al. (1958) at their Station 139 three and one-half miles northwest of Charlevoix under west and southwest winds have been incorporated into the present analysis.

Movement of water from the southwest resulted in an eastward current along the south shore, extending to the inner end of the bay. This was consistently shown by pole, drogue, and dye movements. The drift-bottle data of Ayers et al. (op. cit.) indicate that, from a station three and one-half miles off Charlevoix, the northeast current did not enter the bay. All ten drift bottles released there on 28 and 29 June, 1955, passed to the Straits area, even though winds were from the southwest on the 28th and west on the 29th. It appears that the principal inflow into Little Traverse Bay is a narrow coastal flow, not over three miles in width, coming from the direction of Grand Traverse Bay to the southwest.

As previously mentioned, the current along the south shore extended to the inner end of the bay. Furthermore, the eastward movement of eight poles and drogues set on a line between the cement plant and Harbor Point, on 11 August, indicated that from this line to the head of the bay all surface flow was essentially to the east. West of this line, five drogues and poles released to the southwest of Harbor Point, on 11 July, moved in paths indicative of a flow to the south, which was apparently incorporated into the eastward current along the south shore. Three poles and drogues released on 12 August to the west of Harbor Point, off Forest Beach, did not move south, but instead went northeast to the vicinity of the four-fathom depth contour, and thence east toward the tip of Harbor Point. This alongshore movement, when considered in conjunction with the southward movement found on 11 July, is taken to indicate a divergence located about one and one-half miles off Forest Beach.

Water passing from this divergence past Harbor Point could either have been incorporated into the flattened counterclockwise eddy believed to lie along the north shore east of Harbor Point, or have been carried directly to the head of the bay.

No evidence of surface movement out of the bay was obtained in the areas covered. The consistency of movements toward the head of the bay indicate strongly that there must be subsurface return flow from that region to the divergence off Forest Beach, if not further.

The divergence off Forest Beach was located in a position where at least partial upwelling of lakeward moving deep water could occur. Here the 175-foot deep inner basin of the bay becomes greatly constricted by the northeastward sill protruding from Nine Mile Point. The obstruction formed by the sill and the converging slope from the north shore could force an upwelling of water, of which part could enter the eastward alongshore current toward Harbor Point and part the mid-bay southward surface current emanating from the divergence. Since this upwelled water would not actually represent an escapement from the bay, there must be a continued lakeward movement of the deep water, probably along the extension of the 175-foot basin.

Water passing to the northeast three and one-half miles off Charlevoix did not enter the bay; on the other hand, a coastal flow closer to shore did enter. It appears that a divergence other than that described for the Forest Beach region exists in the outer end of the bay. Since none of the drift bottles from the station off Charlevoix stranded south of Waugoshance Point, this divergence must be well out in the bay mouth. It has tentatively been indicated off Seven Mile Point. Configuration of the bottom topography substantiates this location; the north-south ridge north of Big Rock Point rises to 100 feet and is in excellent position to divide the flow from the southwest. Drogues set at 100 feet on 12 August showed that currents at that depth were in essentially the same direction as those at the surface. It is logical, then, to expect that the 100-foot apex of the ridge might divide the current from the southwest and produce an upwelling behind the ridge and off Seven Mile Point. Upward movement of water in this upwelling would function as a negative pressure which would couple with the positive pressure generated in the head of the bay by currents moving onto land there. The pressure-couple and the orientation of the bay's deep inner basin are well suited to the production of subsurface movement of water from the head of the bay to the upwelling off Seven Mile Point, and the constriction of the deep inner basin is in proper position to provide a partial upwelling in the region off Forest Beach. Water upwelled off Seven Mile Point and moving to the northwest appears to be the only surface escapement of water from the bay.

V. CURRENTS IN THE VICINITY OF THE REACTOR

A primary part of the field operations was the observation, under as many different wind directions as possible, of surface currents in the vicinity of the reactor. It was particularly desired to determine the manner in which the currents are controlled by wind, to permit reasonably accurate forecasting of the direction of flow of water passing the reactor.

Surface currents were measured by observing the movements of current poles and drogues as described in the treatment of the general circulation of Little Traverse Bay. Movements of dye patches used in dilution studies contributed additional information, particularly close to shore in the embayment contiguous with the east side of Big Rock Point, where the effluent channel from the reactor enters the bay.

A. THE ALONGSHORE CURRENTS AND THE BIG ROCK EDDY

Wind and current measurements in the vicinity of the reactor are summarized chronologically in Table II. Studies were made on 15 days, between 25 June and 24 August, when winds were sufficiently steady to permit observations under a given wind over a period of several hours. Data were collected during winds from N, NNE, ENE, E, S, SW, WSW, W, WNW, NW, NNW. The lack of data for winds from the NE, between ESE and SSE, and SSW is due to absence of winds from those directions during our operations.

In Table III, observations of wind and current have been arranged according to wind directions, beginning with north and proceeding clockwise around the compass to NNW. One section of this table contains those observations made to lakeward of the small embayment contained between Big Rock Point and the point at the highway park 1-1/4 miles east of the reactor; the other contains those made within that embayment. The separation has been made because currents within the embayment frequently differed from those outside during the same period of observation, under the same winds.

The orientation of the shoreline at the reactor site is approximately ExN - WxS, based on a line tangent to Big Rock and Nine Mile Points. When the wind was in the quadrant N to E, the main current off the reactor site, lakeward of the small embayment, ran parallel to the shore toward the WxS (out of the bay). When the wind was from WNW, NW, or NNW, this current ran approximately to the WSW, still directed out of the bay but possessing an onshore component. West of Big Rock Point the orientation of the shoreline changes, sloping to the southwest. Under all observed winds except east winds, the out-of-the-bay current passing the reactor turned approximately southwest and followed the shore. On east winds, the current diverged from the shore after

TABLE II

CHRONOLOGICAL OBSERVATIONS OF WIND AND CURRENT
IN THE VICINITY OF THE REACTOR SITE

Date	Location	Wind		Current	
		Direction From	Velocity (mph)	Direction Toward	Velocity (mph)
25 June	1/8 - 1 mi off plant	W	8-12	ExN	0.34
27 June	5/8 mi off plant	WSW	5-10	ExN	0.40
29 June	3/8 - 1 mi off plant	WSW	8-12	ExN	0.72
13 July	1/2 - 1 mi off plant	NNE	20-24	WxS	0.45
21 July	1/4 - 1 mi off plant	S	8-12	NExE	0.46
25 July	0 - 1/4 mi off plant	S	1-3	NNE	0.20
29 July	0 - 1/8 mi off plant	SW	8-12	NWxN	0.32
	1/4 mi off plant	SW	8-12	ExN	0.39
4 Aug	3/8 - 1-5/8 mi off plant	N	4-7	SW	0.58
4 Aug	0 - 1/16 mi off plant	WNW	2	ExN	0.27
	1/4 mi off plant	WNW	2	WSW	0.68
9 Aug	5/16 - 1-3/8 mi off plant	E	10	W	0.46
10 Aug	1/8 mi offshore, 7/16 mi E of plant	NW	8-9	ExN	0.53
	1/4 - 1/2 mi off plant	NW	8-9	SWxW	0.32
15 Aug	3/16 mi off plant	NNW	10-12	WxS	0.09
19 Aug	1/4 mi off park	ENE	4-6	WxS	0.29
24 Aug	1/8 mi off plant	ENE	8-12	SW	0.36
	1/4 - 1-1/4 mi off plant	ENE	8-12	WSW	0.65

TABLE III

WIND AND CURRENT DIRECTIONS OUTSIDE AND INSIDE THE BIG ROCK EMBAYMENT

Outside Bay		Inside Bay	
Wind From	Current Toward	Wind From	Current Toward
N	SW	N	E
NNE	WxS		
NE			
ENE	WSW	ENE	SW*
	WxS		
E	W		
ESE			
SE			
SSE			
S	NExE	S	NNE
SSW			
SW	ExN	SW	NWxN
WSW	ExN		
	ExN		
W	ExN	W	E
WNW	WSW	WNW	ExN
NW	SWxW	NW	ExN
NNW	WxS		

*Appeared to be recurving into eddy.

passing to the westward of Big Rock Point, and continued in a nearly westerly direction.

When the wind was in the quadrant S to W, inclusive, the current was directed into Little Traverse Bay: SW, WSW, and W winds set up eastward currents parallel to shore; S winds resulted in a current which, while being directed into the bay, moved offshore toward the northeast.

In the small embayment between Big Rock Point and the highway park, current directions differing from those to lakeward indicated the presence of an elongate eddy extending from Big Rock to the park. This eddy appeared to reach to lakeward about as far as the line tangent to Big Rock and Nine Mile Points. The observed currents evidencing the existence of this eddy appear in Table III.

The oppositely directed currents within and without the embayment are definite indications of the presence of a small, flattened eddy; the lakeward side ran in the same direction as did the main current outside the embayment,

while the shoreward side necessarily ran in the opposite direction in completing the rotation. On two occasions, under winds from the west and from the south, the eddy was not found. During the west wind, all currents, both inside and outside the embayment, were to the eastward. On the south wind, current outside the embayment was to the NExN, and inside the embayment, NNE. It would not be expected, however, that a south wind would generate an eddy, all transport at this time being directed offshore. The situation observed for the west wind was the only occasion when the eddy did not appear to be operating. There is no reason to believe that it should not operate under a west wind, and its apparent absence on that occasion cannot be explained. Unfortunately, cessation of westerly winds gave no further opportunities to search for it under west-wind conditions. It is likely that it exists most of the time when eastward currents exist. When the wind is such that the currents run essentially away from the shore, it would not be expected that the eddy would be present.

The eddy is not considered to be an important part of the currents in the region of the reactor. It is small and weakly moving; it may be either destroyed or severely modified when the plant effluent discharge begins.

B. WIND CONTROL OF CURRENTS

The surface currents in the region of the reactor originate from the interaction of wind-stress energy input, the rotation of the earth, and local physical or hydrodynamic barriers. The available evidence indicates that a wind of a one to two hours' duration is sufficient to alter an existing current regime.

In considering the manner in which the currents are controlled by the winds, the effect of the rotation of the earth (Coriolis force) must be taken into account. Over the open lake, wind-driven water does not move directly downwind but at an angle to the right of the wind direction. In mid-latitudes, this angle is usually of the order of 45°. Observed currents, however, are frequently found to move in downwind directions other than this 45° deviation. Such behavior is caused by some barrier which impedes the progress of the water initially set in motion by the wind (called the primary transport). Impingement of primary-transport water against the barrier, which may be the shore or another current, results in secondary currents. Secondary current tends to run parallel to the axis of the barrier against which the primary transport has impinged, the direction of flow being determined by the angle at which primary transport encounters the barrier.

The direction of the shoreline at the reactor is essentially ExN - WxS. Currents measured during WNW, NW, NNW, N, NNE, ENE, and E winds were directed westward out of the bay, while those measured during S, SW, WSW, and W winds were directed eastward into the bay. If the initial movement of water is taken to be 45° to the right of the wind direction, the primary transport during observed winds WNW through E (current moving out of the bay) would be as follows:

WNW: 45° primary transport toward shore, approximately normal to shore.
NW through NNE: 45° primary transport toward shore but angled to S - WSW.
ENE and E: 45° primary transport away from shore, angled to WNW and NW.

The primary water transports resulting from NW through NNE winds encounter the barrier formed by the shoreline at less than critical angle and set-up does not occur, the westward secondary current merely sliding along the shore. Winds from the WNW, however, direct water onto the shore at an angle which is nearly normal to the shoreline. On the single occasion when currents were observed under WNW winds, the current was moving out of the bay; it seems probable (discussed below) that currents are likely to be variable under WNW winds, and may be found moving either into or out of the bay.

The primary transports occurring under ENE and E winds would move away from shore, which under these winds does not function as a barrier. However, currents measured during these winds were found to move in a W, WxS, or WSW direction, rather than to the WNW and NW, indicating that secondary currents were also present when these winds were effective. Ayers et al. (1958) found that winds from northeasterly directions tended to create a southward current along the east side of Lake Michigan which passed across the mouth of Little Traverse Bay. The margin of this current probably functions as a barrier against which set-up can occur; this would account for secondary W to WSW currents found under ENE and E winds.

Considering next those winds during which currents were found moving into Little Traverse Bay, the primary transport would be as follows for winds S through W:

S: 45° primary transport away from shore, angled to NE.
SW, WSW, W: 45° primary transport toward shore, angled to E - SE.

In the case of the S wind, the observed current nearly coincided with the theoretical 45° transport, indicating a lack of offshore set-up and a probable absence of secondary currents in the southern half of the bay. On SW, WSW, and W winds, however, the primary transport would be directed onto shore, at an angle of incidence resulting in set-up against shore and a secondary current directed into the bay. When set-up occurs, the secondary current flows geostrophically on the slope of the set-up and in such a direction that the high side of the set-up is on the right-hand side of the current.

Since the observed currents can be satisfactorily explained on the basis of 45° primary transport and secondary currents, it appears possible to predict current directions off the reactor for wind from all directions. Winds from NW around to E generated currents out of the bay; winds from S around to W generated currents into the bay. No observations were obtained during winds from NE, ESE, SE, SSE, or SSW. Probable currents existing under these winds can be predicted, however, on the assumption that primary transport will be

45° or nearly so, and that secondary currents will flow along known or logically-suspected barriers. Under these conditions, NE winds would generate an initial movement to the west, which would likely encounter and be entrained by the southward flow at the mouth of the bay described by Ayers et al. (op. cit.). Winds from ESE would initiate a primary transport to the NNW; there are not sufficient data to ascertain the probable fate of this drift. SE winds would transport water almost directly away from shore, and SSE winds would move it offshore and angled slightly into the bay, with no secondary effects becoming noticeable near the south shore. Since W winds were seen to direct the surface current into the bay, and NW winds direct it out of the bay, winds between W and NW constitute a transition phase, with a shift across this section resulting in a change of about 180° in current direction. Currents under WNW winds, then, would tend to be variable and unpredictable. Similarly, observations showed that E winds generated currents running to the west (out of the bay), while S winds moved water into the bay. A transition phase must also exist between E and S, and although it was not observed, it probably occurs at about SE, where transport is nearly normal to shore. ESE winds should initiate a primary transport out of the bay, and SSE or SSW winds a transport into the bay.

To summarize, water discharged from the plant would enter directly into the small eddy immediately adjacent to the reactor, when conditions were such that the eddy would be operative. The eddy in turn feeds into the main alongshore current which would most probably be as follows under the various winds:

Wind From	Current
NW, NNW, N, NNE, NE, ENE, E	Out of the bay.
ESE	Out of the bay.
SE	Transition phase.
SSE, S, SSW	Into the bay.
SW, WSW, W	Into the bay.
WNW	Transition phase.

C. RELATIONSHIP OF CURRENT VELOCITY TO WIND VELOCITY

Current velocity in lakes is usually considered to be about 2% of the causative wind's velocity. Velocities of the alongshore currents of Little Traverse Bay, however, show a bi-modal relationship to wind velocity; one mode appears to be at about 2% and the other at about 6% of wind velocity (Fig. 5).

Analysis of this situation reveals that the two relationships are dependent upon the previous day's wind direction. When the winds of the observation day and of the preceding day are from the **same** direction, the current moves at about 2% of velocity of the observation-day wind. When wind of the preceding day has been generally opposite to wind of the observation day, the latter's current moves at about 6% of observation day wind velocity. Higher current

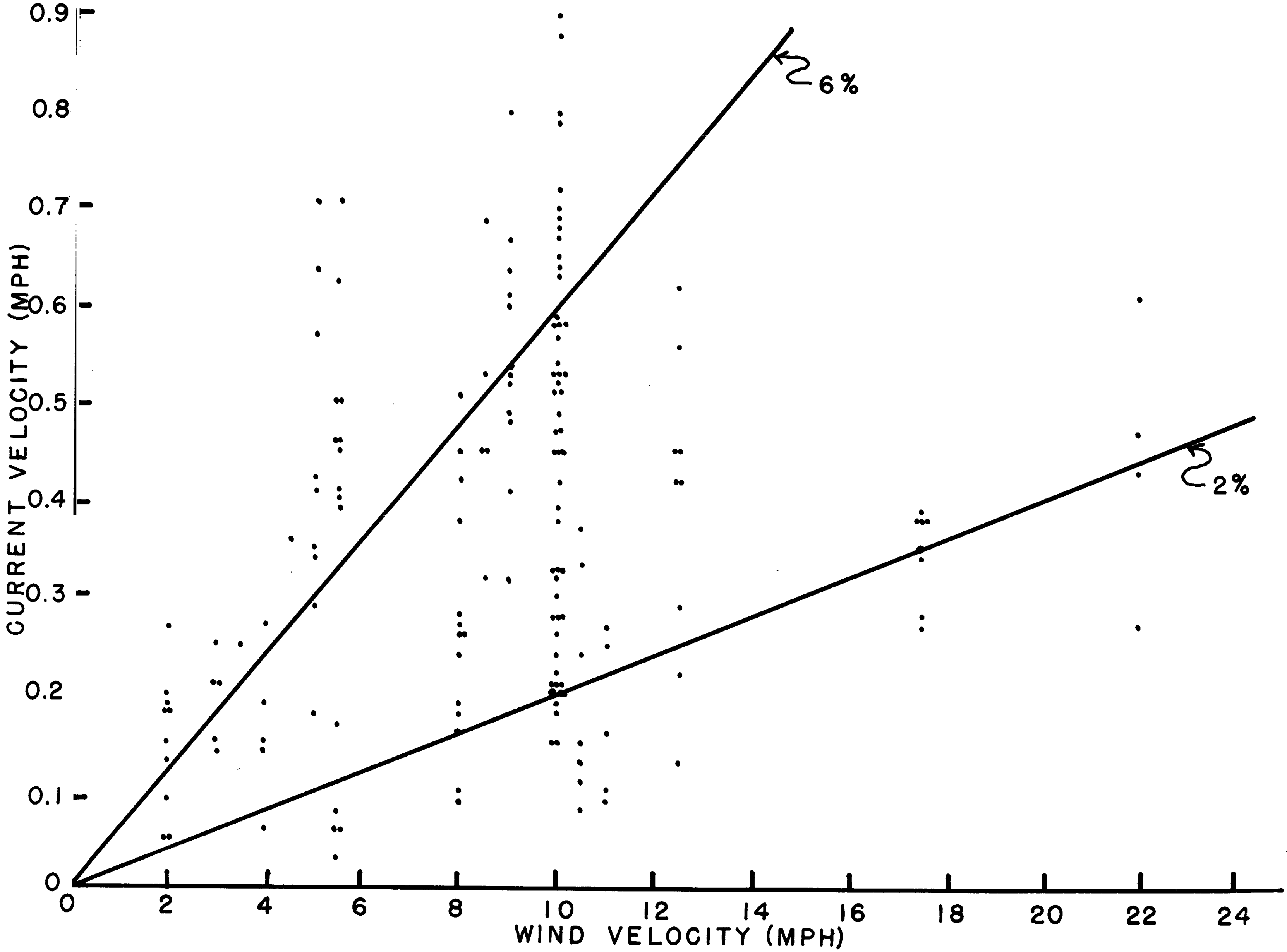

Fig. 5. Relationship of current velocity to wind velocity.

velocities in a new current after a wind change are believed to be a result of the increased efficiency of wind-stress energy input accompanying the higher choppier seas that run during the period when new wind is opposing old current.

D. EXPECTED FREQUENCY OF VARIOUS WINDS

Since the direction of the surface current in the vicinity of the reactor is related to the local wind direction, a knowledge of the expected frequency of winds from the various quarters makes possible a knowledge of the frequency currents to be expected. Hewson and Jones (1959) have compiled five years (1955-1959) of four-hourly wind observations at the USCG Lifeboat Station at Charlevoix, and have arranged these with respect to average frequency of occurrence from each of the eight cardinal directions. Percentage frequencies are given for each of the four seasons, as well as for the entire period. Their compilation is included here as Table IV.

If observations at Charlevoix are representative of wind conditions in the immediate vicinity of the reactor, they should be a convenient tool for estimating the frequency of currents to be expected. A comparison of the Charlevoix data with observations obtained by us during the summer of 1960, however, suggests that winds at Charlevoix may not be representative of winds at the reactor.

All our observations of wind direction were compiled to obtain the frequency of winds from each of the cardinal directions. These frequencies were then compared with the summer average at Charlevoix (Table V, columns 1 and 3). Several significant differences were noted. At Charlevoix the most frequent wind direction was southwest, at the reactor it was west. Secondly, Charlevoix observed about three times as much wind from the southeast as we observed at the reactor (12.6% vs. 4.5%). On the other hand, we observed about three times as much northeast wind as did Charlevoix (15.4% vs. 5.2%).

Since our observations were all made during daylight hours, usually between 0900 and 1800, it was decided that a comparison of our data with Charlevoix observations at 1200 and 1600 might prove more valid since inclusion of the Charlevoix nighttime and 0800 observations might reflect the effects of the land breeze which had usually ceased during our normal work period. The average Charlevoix frequencies computed on this basis appear in column 2 of Table V. This revised compilation has the effect of decreasing the frequency of southeast winds at Charlevoix from 12.6% to 5.4%, which is in close agreement with our 4.5%. The rather large discrepancy in frequency of northeast winds remains, however, as does that between west and southwest. It must be remembered that our observations were made during a single summer and compared with a five-year average, that this average did not include the Charlevoix 1960 data, and that our observations were on a random basis rather than a fixed

TABLE IV

PERCENTAGE FREQUENCY OF OCCURRENCE OF WIND DIRECTION AND CORRESPONDING AVERAGE WIND SPEED BY SEASON
USCG LIFEBOAT STATION, CHARLEVOIX, MICHIGAN

(From Hewson and Jones, 1959)

Wind Direction	Spring, 1955-1959		Summer, 1955-1959		Fall, 1954-1958		Winter, 1955-1959		Entire Period, 1955-1959	
	Freq Dir (%)	Avg Speed (mph)	Freq Dir (%)	Avg Speed (mph)	Freq Dir (%)	Avg Speed (mph)	Freq Dir (%)	Avg Speed (mph)	Freq Dir (%)	Avg Speed (mph)
N	11.6	7.3	8.3	7.7	7.7	13.5	9.5	12.6	9.3	10.0
NE	8.3	6.5	5.2	5.9	5.6	8.2	7.6	5.9	6.7	6.6
E	12.8	4.9	8.6	3.8	8.4	5.4	10.2	4.5	10.0	4.9
SE	10.7	3.9	12.6	3.2	15.3	4.7	14.4	4.2	13.2	4.1
S	10.5	4.4	13.9	4.4	14.2	5.9	12.1	5.7	12.7	5.1
SW	18.5	7.7	25.9	6.5	18.7	12.3	15.5	10.1	19.7	8.9
W	13.1	9.1	9.9	8.5	9.0	14.9	11.9	13.5	11.0	11.4
NW	12.8	10.6	10.3	10.7	15.9	15.7	17.2	13.9	14.0	13.0
Variation	1.5	3.2	4.6	2.1	4.8	3.1	1.2	4.4	3.1	2.8
Calm	0.2	0	0.7	0	0.4	0	0.4	0	0.3	0
	100	6.9	100	6.0	100	9.8	100	9.0	100	8.0

TABLE V

PERCENTAGE FREQUENCY OF WINDS FROM THE VARIOUS DIRECTIONS

Wind Direction	Summer 1955-1959	Summer 1955-1959	Summer 1960
	24-hours Obs.	Obs. at 1200 and 1600	All GLRD Obs.
N	8.3	9.8	12.6
NE	5.2	4.7	15.4
E	8.6	5.3	11.3
SE	12.6	5.4	4.5
S	13.9	8.1	6.3
SW	25.9	39.4	11.6
W	9.9	13.8	24.5
NW	10.3	11.3	10.8
Var.	4.6	1.9	0.3
Calm	0.7	0.3	2.7
	100.0	100.0	100.0

schedule as at Charlevoix. For these reasons strict comparability cannot be implied. The differences in certain of the frequencies, however, particularly the increased number of northeast winds at the reactor, indicate a possibility that there are real differences between the average wind regimes at the two locations. The meteorological station now in operation on Big Rock Point will permit the proper evaluation of this situation as soon as sufficient data have been collected. It is pointed out here as a possibility which should be investigated.

VI. DILUTION STUDIES

The work carried out in this phase of the program was designed to give measures of the natural rates of dilution in the surface waters of Little Traverse Bay. Dilution is the result of mixing processes in the water under conditions of turbulent flow and of eddy diffusion (as opposed to the more simple laminar flow and molecular diffusion). The data have shown that the diminution of the concentration of a tracer dye introduced into the bay waters may be well described as a dilution process, without considering the eddy diffusion mechanism.

A. METHODS

Because the purpose of this work was to give dilution information for the evaluation of possible hazards associated with the operation of a nuclear power reactor, the experiments and measurements were designed to give conservative values of the dilution data. It is necessary to give a description of the techniques to indicate the significance of the results obtained.

A fluorescent dye solution (with specific gravity adjusted to compare with the warmed reactor effluent) was introduced into the bay water, and the dye concentration was monitored with a fluorometer to obtain the time rate of dye concentration decrease. The fluorescent dye was one pint of a stock solution of Rhodamine B in 40% acetic acid solution, mixed with three quarts of methanol. This dye solution would float in the upper layer of water, corresponding to the expected behavior of the warmed reactor effluent. All the dye stayed in the upper 10 feet of the water, with the majority of it less than 3 feet from the surface. The fluorometer permitted the measurement of dye concentrations down to one part per billion (weight of dry dye in water solution).

After the dye was introduced, the research vessel was slowly coasted through the resultant dye patch while dyed water was continuously pumped through the fluorometer. Successive passes through the dye were made, and the maximum observed concentration recorded on each pass. By recording the concentration maxima, a minimum rate of dilution is obtained (dilution of the dye-patch center was largely a matter of dye being diluted with dyed water). A typical sequence consisted of passes through the densest part of the dye patch every ten or twenty minutes until the dye patch became too diffuse to measure accurately.

The path of the dye patch was observed, and if a prolonged sequence of measurements was required, a second dye patch was introduced at the leading edge of the first patch when the latter was becoming too diffuse to measure.

The dilution of the second patch was followed and if necessary a third patch was made. The total dilution occurring through the sequence of patches was the product of the dilution observed for the first patch multiplied by that of the second patch, multiplied by that of the third, etc. A sequence of any number of patches may be treated in the same manner.

B. THEORETICAL CONSIDERATIONS

Considering the dye concentration as a function of time C(T) given in the manner

$$C(T) = C_o \; f(T) \tag{1}$$

where C(T) is maximum concentration observed in the dye patch at time T, and C_o is the initial concentration. We may define the dilution as

$$D(T) = C_o/C(T) = 1/f(T) \tag{2}$$

From relation 2 it is evident that the determination of the maximum values of the dye concentration [considered to be C(T)] will give minimum values for the dilution D(T). Figures 6, 7, and 8 show representative dilution curves obtained during the series of dilution measurements.

From the curves, it is seen that the dilution obeys the relation

$$\log D(T) = aT = - \log f(T) \tag{3}$$

where a is interpreted as

$$a = \frac{1}{t}\log r_t \tag{4}$$

Equation (1) may therefore be written as

$$C(T) = C_o r_t^{-(T/t)} \tag{5}$$

In the above expressions, t specifies the dilution period (i.e., r_t denotes a dilution by a factor r in a period of t minutes).

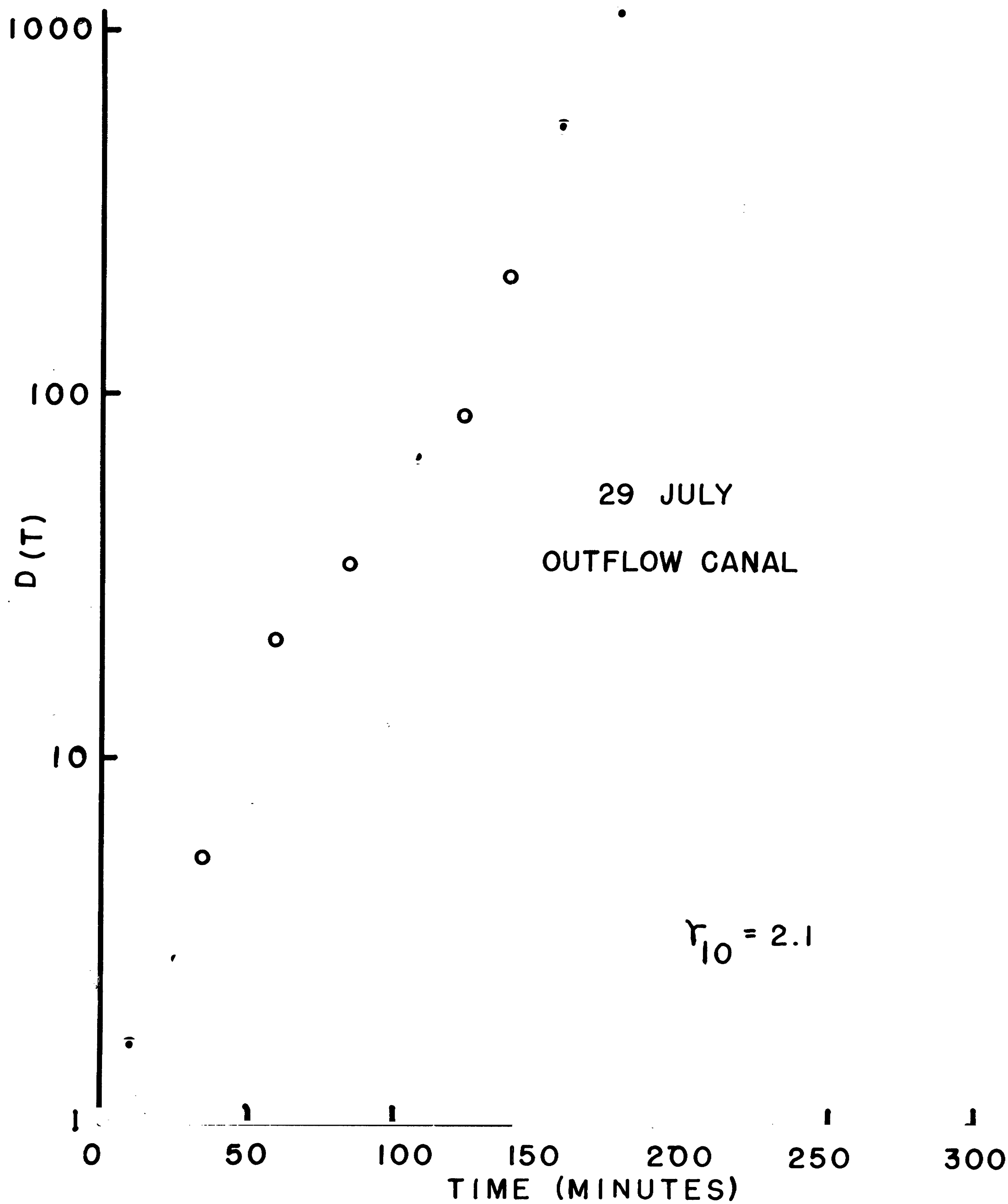

Fig. 6. Representative dilution curve: July 29, at Outflow Canal.

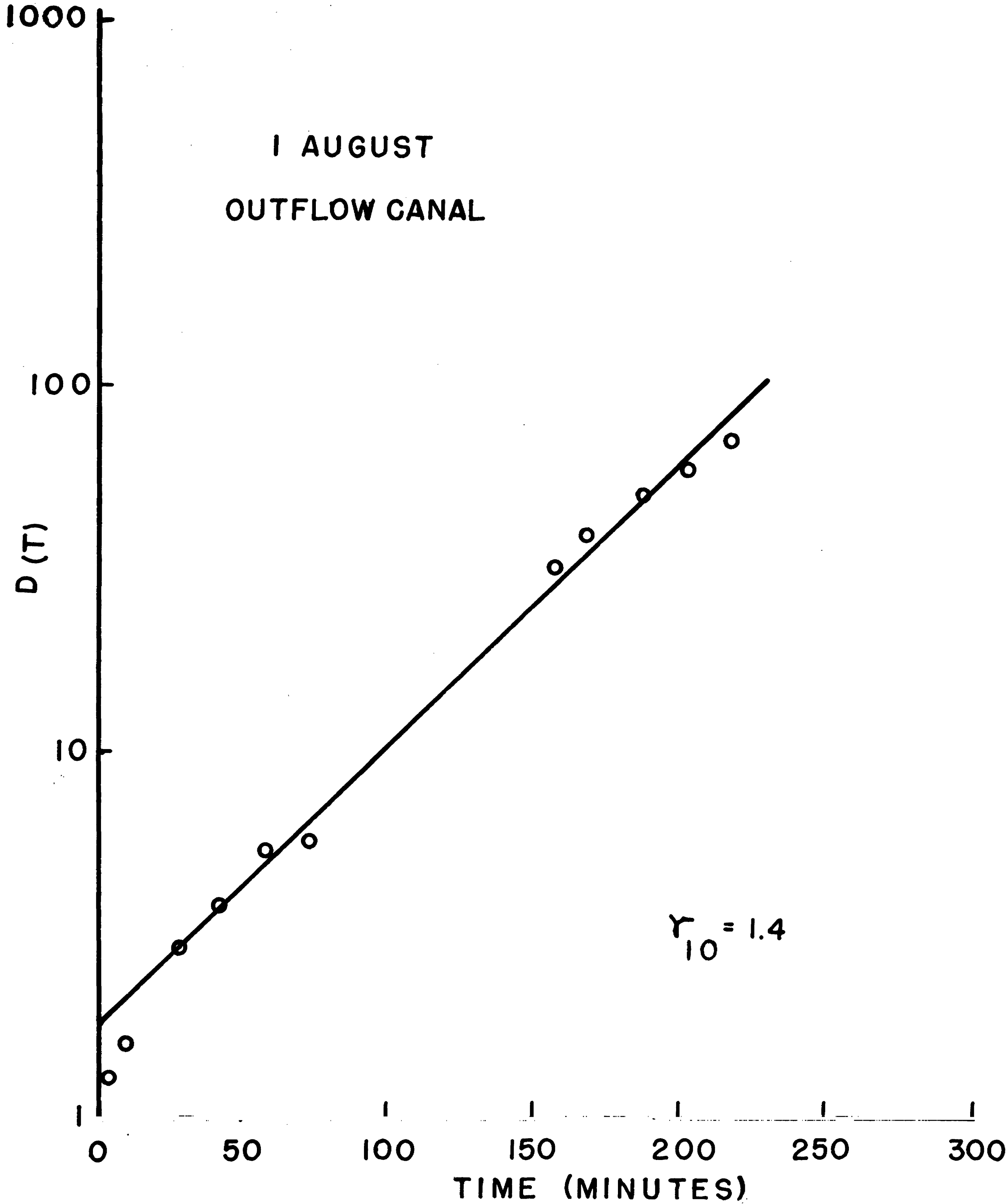

Fig. 7. Representative dilution curve: August 1, at Outflow Canal.

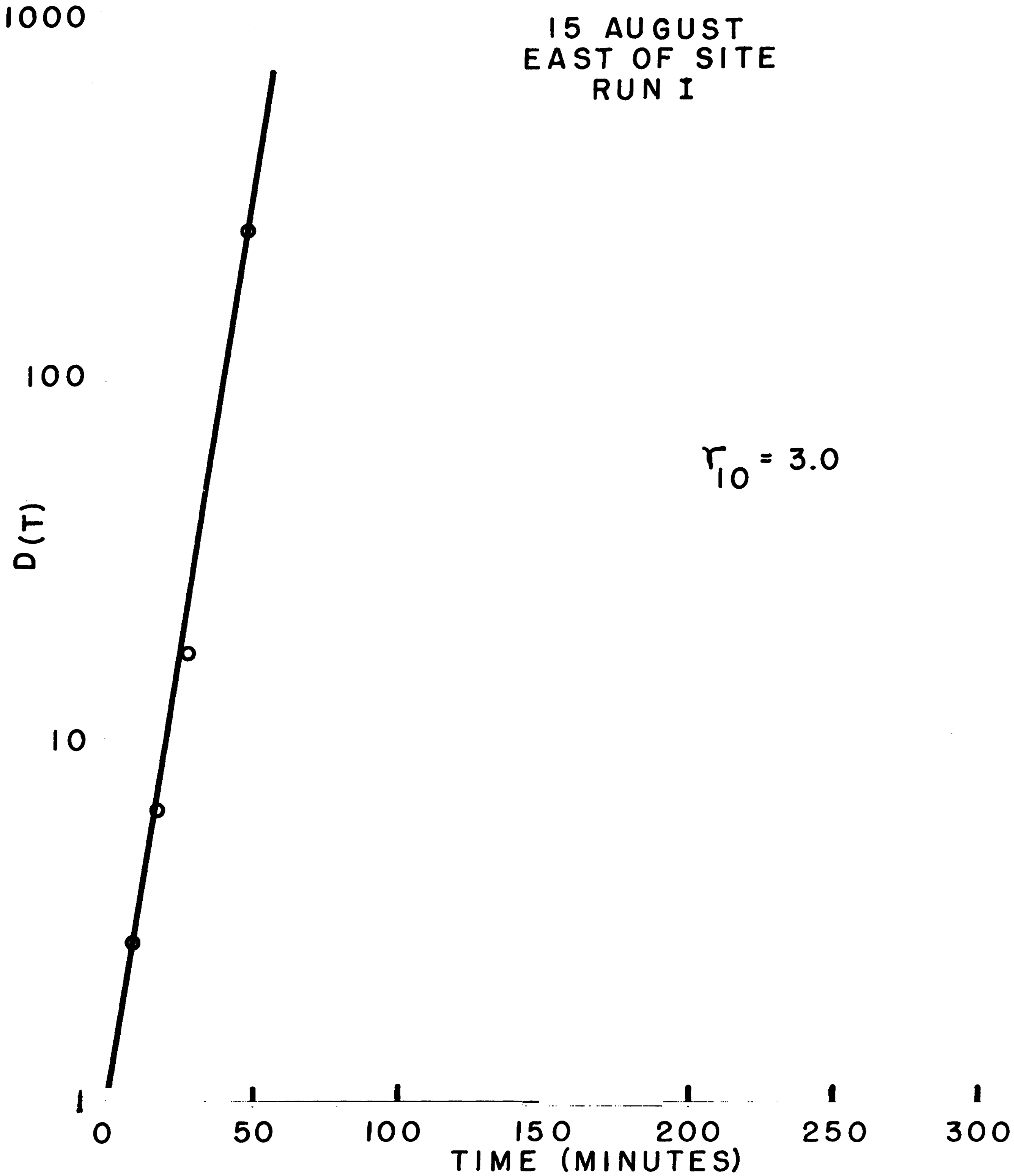

Fig. 8. Representative dilution curve: August 15, off Roadside Park.

Let us now consider the mechanics of the dilution process to determine the significance of r_t. The total amount of dye in the dye patch being a constant, if we assume a uniform concentration through the patch, the product of the dye concentration, C, and the total volume of the dye solution, V, is a constant

$$CV = B \tag{6}$$

Considering the dilution to proceed at a constant rate, the expression for the volume of the dye patch becomes a geometric series in time and may be written

$$V(T) = V_o \, r_t^{(T/t)} \tag{7}$$

where V_o is the initial volume of the dye patch, and r_t is the dilution ratio. Substituting Eq. (7) into Eq. (6), the expression for the dye concentration as a function of time becomes

$$\begin{aligned} C(T) &= (B/V_o) \; r_t^{-(T/t)} \\ &= C_o \, r_t^{-(T/t)} \end{aligned} \tag{8}$$

This is the same expression as that obtained from the dilution measurements [Eq. (5)] and demonstrates that we may consider the dilution to proceed as a simple geometrical process.

The assumption of uniform dye concentration, used in writing Eq. (6), is closest to real conditions when the uniform concentration considered is the mean concentration. In our practice, however, the concentration used is the maximum, and the dilution ratios that result are conservative.

C. RESULTS

The frequency distribution for the values of r_t which have been obtained from the data collected under winds of 0 to 10-12 mph is shown in Table VI. The corresponding distribution of observed current speeds from the motion of the dye patches under these light winds is shown in Table VII. The relation of the dilution ratio to the wind speed at the time of measurement is shown in Fig. 9. Figure 9 also gives two curves describing the relationship (which have been fitted to the data by the least-squares method). The dilution ratio has been found to be independent of both the current speed and the distance traveled by the dye patch.

TABLE VI

FREQUENCY DISTRIBUTION OF CURRENT SPEED (24 OBSERVATIONS)

(Under winds of 0 to 10-12 mph)

Current Speed (mph)	No. of Observations	Current Speed (mph)	No. of Observations	Current Speed (mph)	No. of Observations
.09	1	.27	2	.57	1
.10	1	.29	1	.64	1
.15	1	.31	1	.65	1
.16	1	.34	1	.68	1
.18	1	.35	1	.71	1
.20	1	.38	1	1.05	1
.21	2	.41	1		
.25	1	.42	1		

Avg = 0.34 mph

TABLE VII

FREQUENCY DISTRIBUTION OF DILUTION RATIOS (24 OBSERVATIONS)

(Under winds of 0 to 10-12 mph)

Dilution Ratio (r_{10})	No. of Observations	Dilution Ratio (r_{10})	No. of Observations
1.4	3	2.0	2
1.5	3	2.1	3
1.6	3	2.6	2
1.7	2	2.9	1
1.9	1	3.0	3
		3.2	1

Avg = 2.058 ~~mph~~

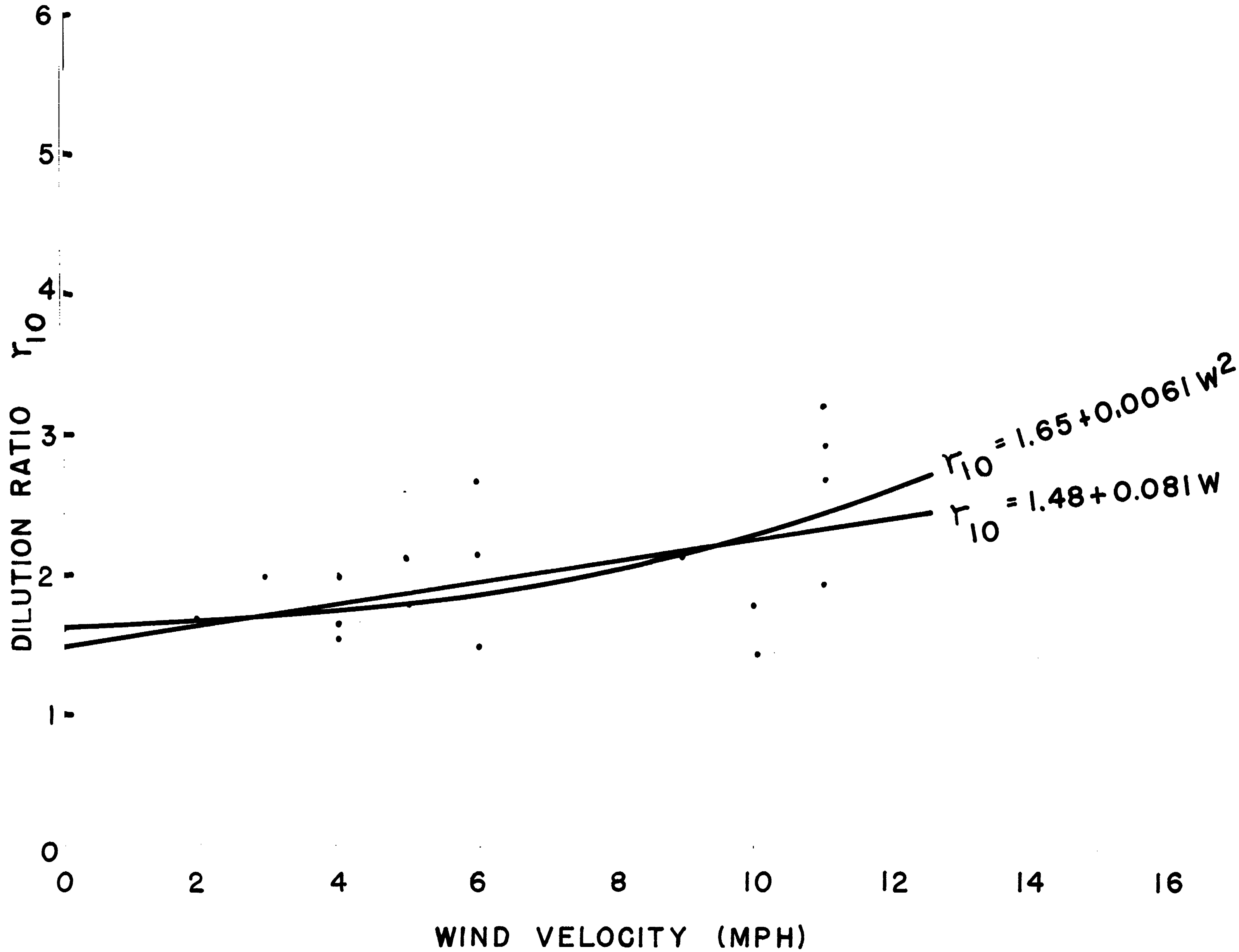

Fig. 9. Relationship of dilution ratio to wind velocity.

Under winds up to 10-12 mph, the average value of the dilution ratio in the alongshore waters between Petoskey and Charlevoix is 2.0 for $t = 10$ min; the range of values for r_{10} is from 1.4 to 3.2. The average value of the current speed in the waters along shore is 0.34 mph, with a range of values between 0.08 mph and 1.05 mph. The relations between the dilution ratio and the wind speed are given by:

$$r_{10} = 1.48 + 0.081\ W \tag{9a}$$

$$r_{10} = 1.65 + 0.0066\ W^2 \tag{9b}$$

Equation (9b) gives a slightly better statistical fit to the data than does (9a) (when using the least-squares criterion), but the value of r_{10} predicted for zero wind speed by (9a) is better than that predicted by (9b).

D. DISCUSSION

One of the most difficult aspects of research is that of determining the extent to which experimental observations may be extrapolated for use in the prediction of future events. To this end, the reader is here informed of some of the anomalous conditions encountered in the measurements, and an interpretation of the data which has been obtained from this investigation.

The first point to be considered will be the choice between Eqs. (9a) and (9b) which relate the dilution ratio to the wind speed. Strictly, the W^2 relation is a better statistical fit to the experimental data, but (9a) does provide more conservative figures for the prediction of the dilution ratio expected under varying wind conditions. No experimental measurements were carried out in winds greater than 10-12 mph, but experience in other areas has shown that the W^2 relationship is not unlikely. It is therefore suggested that Eq. (9a) be used for future predictions in which a definitely conservative figure for the predicted values of r_{10} is needed. In cases where a more realistic r_{10} is useful, Eq. (9b) should be used.

Second, the data show that the <u>dilution ratio</u> is independent of both the distance of travel and the current speed of the dye patch. The <u>amount of dilution</u>, however, is dependent upon the time available for dilution as the effluent waters from the reactor proceed to the localities of interest, namely, Charlevoix, Petoskey, and the Penn-Dixie plant. Time for dilution (travel time) must be determined from the expected current speed and the distance the effluent waters must travel. Since the dilution is given by

$$D(T) = C_0/C(T) = r_{10}^{T/t} \tag{10}$$

short travel times will yield small dilutions and higher concentrations of the effluent waters reaching the three localities of interest. Reasonably direct paths of motion for the effluent waters on their way from the reactor site to the localities of interest give distances of 5.5 miles, 9 miles, and

12 miles to Charlevoix, Penn-Dixie, and Petoskey, respectively. The remaining problem, then, is to ascertain the meaning of the current speed used for the computation.

The current speeds reported here are computed from the distance traveled along the path of motion during the observation period. Wind-driven currents almost never move in straight lines. Curvatures of path are forced upon the alongshore currents by shoreline irregularities and curving paths are produced by convergences and divergences. Current velocity computed along the trajectory of a water particle is larger than the net transport velocity computed along a straight line from the particle's initial position to its final one. Current velocities, being larger, provide less travel time during which dilution can take place, and consequently yield smaller more conservative dilution values.

Nearly all the current velocities given in this report were obtained from drogues and current poles. Both these devices receive a small direct impetus from wind on their emergent parts, and consequently move a few per cent faster than did the dye patches. This was anticipated and the velocities have not been corrected for their average 3% overspeed.

To summarize, conservative measures have been used wherever possible in the dilution computations of this section.

The "average" dilutions at Charlevoix (D_{Ca}), Petoskey (D_{Pa}), and at the cement plant (D_{Da}) under winds up to 10-12 mph have been determined by using the average value of the measured current speed (to determine the dilution times from the respective water-transport distances of 5.5 miles, 12 miles, and 9 miles) together with the average value of the dilution ratio. These values for lighter winds are given in Table VIII.

TABLE VIII

AVERAGE DILUTIONS OF REACTOR EFFLUENT ARRIVING AT CHARLEVOIX, PETOSKEY, AND THE PENN-DIXIE PLANT UNDER LIGHT WINDS

Conservative Factors Used Throughout
(Winds 0 to 10-12 mph)

Current Speed (mph)	Dilution Ratio (t = 10 min)	Dilutions Computed for Charlevoix, Petoskey, and the Penn-Dixie Plant
$v_{av} = 0.34$	$(r_{10})_{av} = 2.0$	$D_{Ca} = 1.6 \times 10^{29}$ $D_{Pa} = 6.6 \times 10^{63}$ $D_{Da} = 7.3 \times 10^{47}$

VII. OPERATIONAL ESTIMATES OF DILUTIONS AT CHARLEVOIX, PENN-DIXIE, AND PETOSKEY

The studies reported above were all carried out under summer conditions. There is at present no reason to think that the results obtained are not representative of other seasons also. It has already been pointed out that conservative factors have been employed in the computations of "average" dilutions expected at Charlevoix, Petoskey, and at the Penn-Dixie cement plant under light winds. It is believed that the cumulated conservatism in our dilution computations is more than sufficient to compensate for any special-case summer conditions that were not observed, or for conditions inherent in other seasons for which there are no data.

Relationships that have come out of our studies make it possible to outline a procedure by which operations personnel at the reactor can make day-to-day estimates of the dilutions undergone by reactor effluent waters at the times of their arrival at Charlevoix in westward (out-of-the-bay) currents or at Penn-Dixie or Petoskey on eastward currents. The procedure begins with wind velocities recorded at the lowest level of the meteorological tower at the site. Section V. B indicates the winds under which westward and eastward currents may be expected.

For Charlevoix on westward currents: The mean wind velocity in mph of the preceding four hours is substituted into Eq. (9b) of Section VI. C to obtain r_{10}

$$r_{10} = 1.65 + 0.0066\ W^2$$

Mean current velocity can be obtained as 2% or 6% of mean wind velocity (see Section V. C). The 5.5-mile water distance to Charlevoix divided by current velocity will give probable travel time in hours. Travel time, converted to minutes and divided by 10, yields T/t needed for the dilution equation [Eq. (10) of Section VI. D]. Equation (10) is then solved. This process is illustrated in Table IX.

For Penn-Dixie and Petoskey on eastward currents: The same procedure as for Charlevoix is followed, except that mean wind velocities of the preceding six hours (Penn-Dixie) or eight hours (Petoskey) are used with water distances of nine miles and 12 miles, respectively, to obtain travel time T.

VIII. MOST HAZARDOUS CONDITIONS

Charlevoix is the nearest sensitive point-of-interest. The distance to Charlevoix is short. The configuration of shoreline between the reactor and Charlevoix is such that winds from the WNW, NW, NNW, and N provide the most direct current movement of reactor effluent to Charlevoix. Not only do the above winds move effluent along the shore, they hold it against shore between Point McSauba and Charlevoix.

In Section V. C it was pointed out that current velocities after a wind reversal are about 6% of wind velocity, compared to about 2% for unidirectional winds.

Current velocities will increase with higher winds, and travel times available for dilution will be decreased, resulting in lessened dilution.

Dilution ratios increase with increased winds, but not in proportion to the decrease of travel time, and this effect is overwhelmed by that of decreased travel time.

Most hazardous conditions, in terms of effluent reaching a water intake after minimum dilution, would occur at Charlevoix under high northwesterly or northerly winds developing after a wind reversal from southerly winds.

To assess as realistically as possible the degree of dilution to be expected at Charlevoix under such conditions, Table IX has been prepared. These computations are realistic in that (1) the direct shortest current path is the one actually expected, (2) the relation of current velocity to wind velocity is derived from local data, and (3) the more realistic Eq. (9b) is used instead of the more conservative Eq. (9a). The only conservative factor involved is that stemming from the use of the maximum concentration of the dye patch in deriving Eq. (10)(Section VI. D). Comparison of Table VIII and the 5-mph wind line of Table IX shows that for Charlevoix the realistic estimate of probable most hazardous condition is only slightly lower than the ultraconservative "average."

The intake of the Penn-Dixie cement plant is the second-nearest point of interest. The most direct reasonable current path from the reactor to Penn-Dixie is nine miles long. Penn-Dixie is located east of the reactor, and the most hazardous wind directions would be those that tend to hold the reactor effluent against the south shore of the bay while driving it eastward. Such winds are those from the SW, WSW, and W. And, again, these winds would be most hazardous if they rose to high velocities soon after a reversal of wind direction from northerly or easterly directions to these southwesterly or westerly directions. Table X presents our assessment of dilutions at the

TABLE IX

ASSESSMENT OF PROBABLE MOST HAZARDOUS DILUTION CONDITIONS AT CHARLEVOIX

Realistic Factors Used Wherever Possible

Wind, W, mph	r_{10} [from Eq. (9b)]	T (hr) (5.5 mi ÷ 6%W)	T (min)	÷ 10 = T/t	$D_{(T)} = r_{10}^{T/t}$
1	1.7	91.7	5502	550.2	6.2×10^{126}
5	1.8	18.3	1098	109.8	1.1×10^{28}
10	2.3	9.2	552	55.2	9.3×10^{19}
20	4.3	4.6	276	27.6	3.0×10^{17}
30	7.6	3.1	186	18.6	2.4×10^{16}
40	12.2	2.3	138	13.8	9.8×10^{14}
50	18.2	1.8	108	10.8	4.1×10^{13}

TABLE X

ASSESSMENT OF PROBABLE MOST HAZARDOUS DILUTIONS AT THE PENN-DIXIE INTAKE

Realistic Factors Used Wherever Possible

Wind, W, mph	r_{10} [from Eq. (9b)]	T (hr) (9 mi ÷ 6%W)	T (min)	÷ 10 = T/t	$D_{(T)} = r_{10}^{T/t}$
1	1.7	150	9000	900	2.5×10^{207}
5	1.8	30	1800	180	8.9×10^{45}
10	2.3	15	900	90	3.6×10^{32}
20	4.3	7.5	450	45	3.2×10^{28}
30	7.6	5.0	300	30	2.7×10^{26}
40	12.2	3.8	228	22.8	5.9×10^{24}
50	18.2	3.0	180	18	4.8×10^{22}

Penn-Dixie intake under the conditions outlined above. Again, comparison of Table VIII to the light-wind section of Table X indicates that most hazardous conditions under light winds are only slightly lower than the ultraconservative "average" computed for light winds.

The city of Petoskey is the third of the localities of interest. At the date of writing we knew of no water intakes there, but there are the usual waterfront activities and a public boat basin. Since Petoskey lies east of the Penn-Dixie plant, the same winds that are most hazardous for Penn-Dixie will be most hazardous for Petoskey (again under the same high-winds after wind-reversal conditions). Table XI gives our assessment of dilution conditions at Petoskey under the conditions outlined.

TABLE XI

ASSESSMENT OF PROBABLE MOST HAZARDOUS DILUTION CONDITIONS AT PETOSKEY

(Realistic Factors Used Wherever Possible)

Wind, W, mph	r_{10} [From Eq. (9b)]	T(hr) (12 mi ÷ 6%W)	T (min) ÷ 10	= T/t	$D_{(T)} = r_{10}^{T/t}$
1	1.7	200	12000	1200	3.5×10^{276}
5	1.8	40	2400	240	1.8×10^{61}
10	2.3	20	1200	120	2.6×10^{43}
20	4.3	10	600	60	1.0×10^{38}
30	7.6	6.7	402	40.2	2.6×10^{35}
40	12.2	5	300	30	3.9×10^{32}
50	18.2	4	240	24	1.7×10^{30}

IX. SUMMARY

Little Traverse Bay is surrounded by relatively high and uneven topography which resulted from the Port Huron and Valders substages of the Wisconsin glaciation. The bathymetry of the bay reflects both the glaciation and an earlier process of irregularity development, probably the solution of salt beds from the underlying Salina rock strata and consequent collapse and recementing of the rocks. Maximum depths more than 300 feet are located in a small area about two miles north of Big Rock Point.

The majority of the submerged area off Big Rock Point is covered by a dense cobble and boulder pavement which overlies red glacial till. In a limited area near Big Rock Point itself limestone bedrock strata are exposed.

The over-all circulation pattern of Little Traverse Bay is incompletely worked out, but it appears to involve (under prevailing winds) a substantial subsurface water movement from the head of the bay to near the bay mouth where a major upwelling in the north central portion of the bay brings water to the surface.

Currents in the vicinity of the reactor site are almost altogether eastward or westward alongshore currents. Shoreline configuration is such that winds from NW through N tend to hold the outflowing current against shore all the way to the Charlevoix water intake. Winds from the SW through W tend to hold the inflowing eastward currents against the shore all the way to the Penn-Dixie intake and Petoskey. Transition phases resulting in reversal of current direction accompany winds from the SE and WNW. A minor elongate eddy appears to be situated, under most winds, in the embayment between Big Rock Point and the highway park; this eddy is driven by the main alongshore current and produces extremely local reversed current directions along the shore in front of the reactor site. This eddy is considered unimportant in the dilution properties of the area, and there is doubt that it will survive when the effluent flow from the reactor comes into operation.

Current velocities in the main alongshore currents are about 2% of the mean wind velocity, when winds have been essentially unidirectional on the observation day <u>and</u> the preceding day. They appear to be about 6% of mean observation-day wind velocity when wind of the preceding day has been approximately opposite to that of the observation day. Two equations relating the dilution ratio to wind velocity have been derived.

A limited amount of evidence indicates that wind regimes at Big Rock Point are not exactly the same as those at Charlevoix. It is suggested that the settling of this point might well be an initial project of the program of meteorological observations at Big Rock.

Detailed studies of the dilutions of dye patches placed in the alongshore currents have produced a series of relationships which make possible the assessment of dilutions undergone by reactor effluent water by the time it reaches Charlevoix, Penn-Dixie, and Petoskey. Under "worst" realistic conditions (50-mph wind and 3-mph current) dilutions at the three points of interest are: Charlevoix 4.1×10^{13}, Penn-Dixie 4.8×10^{22}, and Petoskey 1.7×10^{30}. Dilutions increase rapidly under lesser winds and exceed 10^{100} (at Charlevoix) and 10^{200} (at Penn-Dixie and Petoskey) under 1-mph winds.

X. REFERENCES

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BIG ROCK NUCLEAR POWER PLANT

HYDROLOGICAL SURVEY

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ORA Project 04016

under contract with:

CONSUMERS POWER COMPANY
JACKSON, MICHIGAN

GREAT LAKES RESEARCH DIVISION
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INSTITUTE OF SCIENCE AND TECHNOLOGY
THE UNIVERSITY OF MICHIGAN
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I. INTRODUCTION

This report summarizes the results of studies carried on during the summer of 1960 in Little Traverse Bay of Lake Michigan. The studies, supported by Consumers Power Company, were designed to obtain a variety of data relevant to the operation of a nuclear reactor power-generation facility at Big Rock Point at the south side of the mouth of Little Traverse Bay.

Several persons of the Great Lakes Research Division of The University of Michigan's Institute of Science and Technology have participated in the gathering and processing of the data and in the preparation of this report. Their names, and the sections of the report for which they were primarily responsible, are:

Vincent E. Noble, Associate Research Physicist, Section VI;
Charles F. Powers, Associate Research Oceanographer, Sections IV, V;
William E. French, Assistant Research Geologist, Section III;
John C. Ayers, Research Oceanographer, Sections I, II, VII.

Dr. Ayers also served as over-all director of the studies and as general editor of the report.

James R. Stockard and Thomas Rodeheffer, as summer assistants, contributed materially in the field phases of the studies.

Messrs. Robert D. Allen and A. L. Bethel, of Consumers Power Co., very kindly provided help in our orientation to the problem, and in furnishing technical information.

II. TOPOGRAPHY AND BATHYMETRY OF LITTLE TRAVERSE BAY

Little Traverse Bay is a triangular embayment of Lake Michigan and is situated in Charlevoix and Emmet Counties in the northwestern portion of the Lower Peninsula of Michigan. The bay is centered at approximately 45°24' north latitude and 85°00' west longitude and is about 12 miles by 10 miles in its greatest dimensions. For the purpose of this study, the mouth of the bay is taken to be along a line from Big Rock Point, in Charlevoix County, on the south shore to Seven Mile Point, in Emmet County, on the north shore.

The shoreline of the bay is relatively regular. Small points tend to occur in series which alternate with longer stretches of smooth shoreline. Two series of small points are present along the south shore; one series is situated between Big Rock Point and Nine Mile Point, the other is in the adjoined waterfront areas of Petoskey and Bayview. On the north shore another series of small points is situated about mid-way between Harbor Springs and Seven Mile Point.

The major shoreline feature of the bay is a large peninsula, Harbor Point, at Harbor Springs. This peninsula is about a mile long and about 0.4 mile in width at its base. It arises from the north shore at Harbor Springs and extends into the bay in a direction from northwest to southeast.

Along most of its perimeter the bay is surrounded by hills rising from 300 to 600 feet above the level of the bay. These hills are morainic relics of the Port Huron stage of the Wisconsin glaciation and have been subject to some modification by the later Valders glaciation which closed the Wisconsin glacial age.

The topography of the area around Little Traverse Bay is sufficiently well indicated by Fig. V-7 of Part B, Consumers Power Company Preliminary Hazards Summary Report, which will not be duplicated here.

The underwater topography, or bathymetry, of Little Traverse Bay is not presented in the Preliminary Hazards Summary Report and is presented here (Fig. 1) because of its indirect bearing upon certain of the features of the over-all water circulation in the bay.

The bathymetry of Little Traverse Bay is characterized by submerged slopes of irregular width which descend into the depths of the bay, and by a high degree of irregularity of the bottom topography. Maximum depth in the bay occurs in a small area in the bay mouth where, about two miles north of Big Rock Point, depths in excess of 300 feet are charted. About seven miles north of Big Rock Point lies an irregular north-south ridge which is extensive at 150 feet and has only 100 feet of water over its apex.

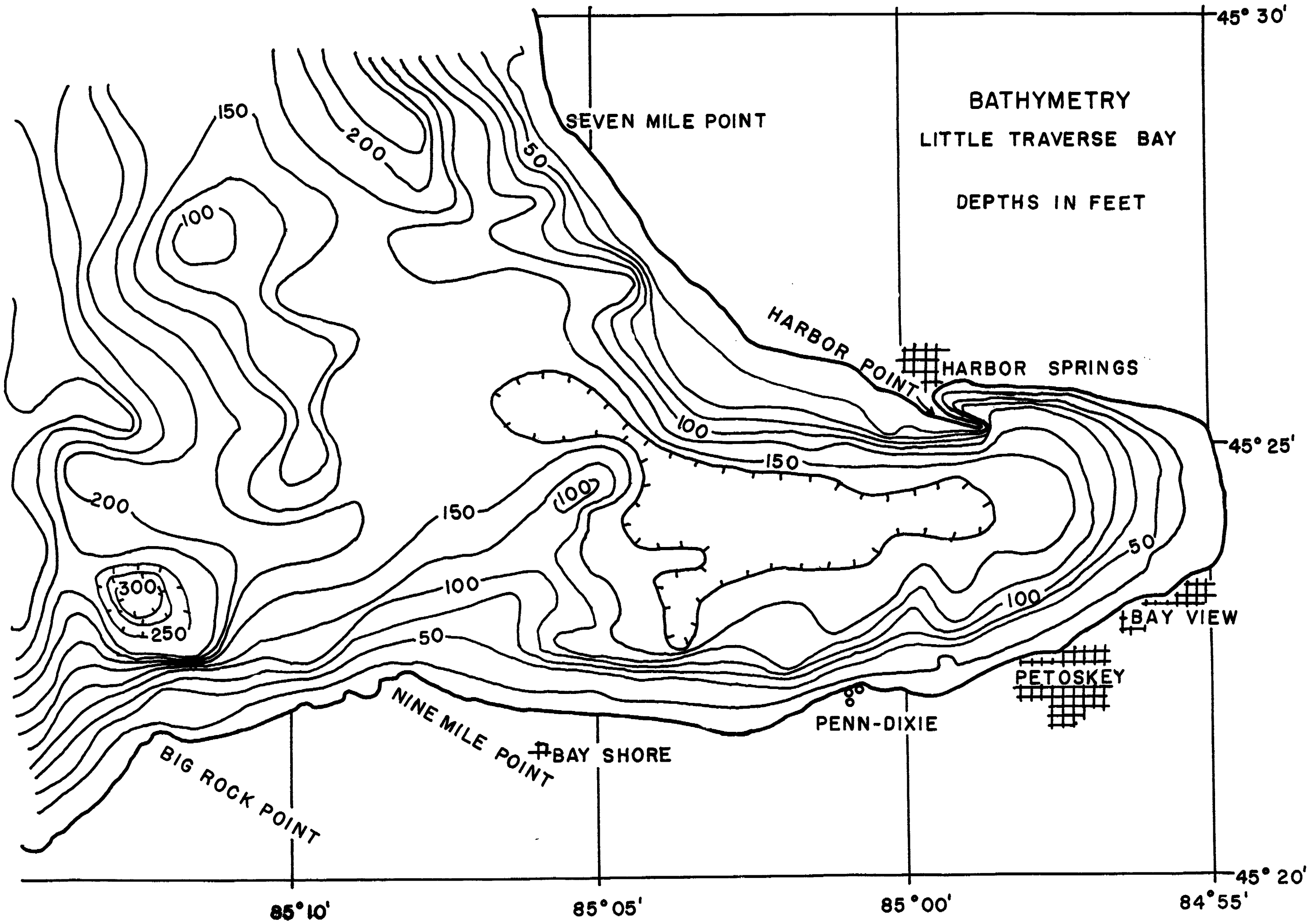

Fig. 1. Bathymetry of Little Traverse Bay.

Protruding northeastward from Nine Mile Point is a partial "sill" which at depths less than 125 feet is continuous for about two-thirds the width of the bay. Depths less than 100 feet occur in a small area at the outer end of the sill.

A relatively large portion of bay-bottom lying at depths greater than 175 feet extends along the axis of the bay from north of Bay Shore to north of Petoskey. This secondary deep portion has a large tributary-like extension reaching toward the south and its west end is severely constricted by the outer end of the sill reaching northeast from Nine Mile Point. The head of the tributary-like southward extension lies only about a mile from shore between Bay Shore and the Penn-Dixie Cement Company plant; here the bottom drops steeply from 50 feet to more than 175 feet. Similar but less pronounced trough-like landward extensions of deeper water lie about a mile north and west of the Penn-Dixie plant and about a mile north and west of Petoskey. These troughs and the large deep water "tributary" are believed to play roles in the normal westerly-wind circulation of the waters of the bay.

III. OFFSHORE GEOLOGY AT BIG ROCK POINT

As an ancillary operation to the current and dilution studies made in the vicinity of the Big Rock Point Reactor Site, a limited survey of the underwater geology was made.

The primary purpose of this survey was to investigate the feasibility of underwater geological mapping by means of SCUBA diving. However, these dives yielded a limited amount of information about the offshore geology near the plant site which may be of interest as being correlative to wells bored on the site.

The survey consisted of four traverses made at right angles to the shoreline in the area from Big Rock Point to the east side of the Reactor Site clearing and extending 2000 feet out into the lake. Each traverse was made by laying a 2000-foot length of line from the shore out along the lake bottom and inspecting the bottom by swimming along this line. The line was marked at 50-foot intervals to enable sample location. The samples and field notes were correlated with fathometer records made along each line at the time it was being laid.

The accompanying diagram (Fig. 2) shows the four sonic profiles obtained by recording fathometer and a tentative correlation along their outer ends. The main feature illustrated is the greater declivity off Big Rock Point, which indicates that the point does not continue very far offshore.

There is a well defined valley which begins between lines II and III, trends northeast across line III, and leaves the area between the outer ends of lines III and IV. The head of this valley may be correlative with the small embayment on the west edge of the Reactor Site.

The limestone outcrop on line I is clearly seen as a series of step-like drops in the bottom profile. Marked irregularities in the profile of line IV indicate the location of the glacial till outcrops. In addition, the sonic profiles indicate the presence of many boulders of about the same size as the Big Rock.

A contour map of the underwater areal topography was included with the preliminary report: "Preliminary Geological Survey off Big Rock Point," Memo from W. E. French to A. L. Bethel, October, 1960.

According to the literature summary by Pohl (1930), the Big Rock Point area is underlaid by rocks of the Traverse formation of Devonian age. This formation consists of a series of shaley and cherty limestones.

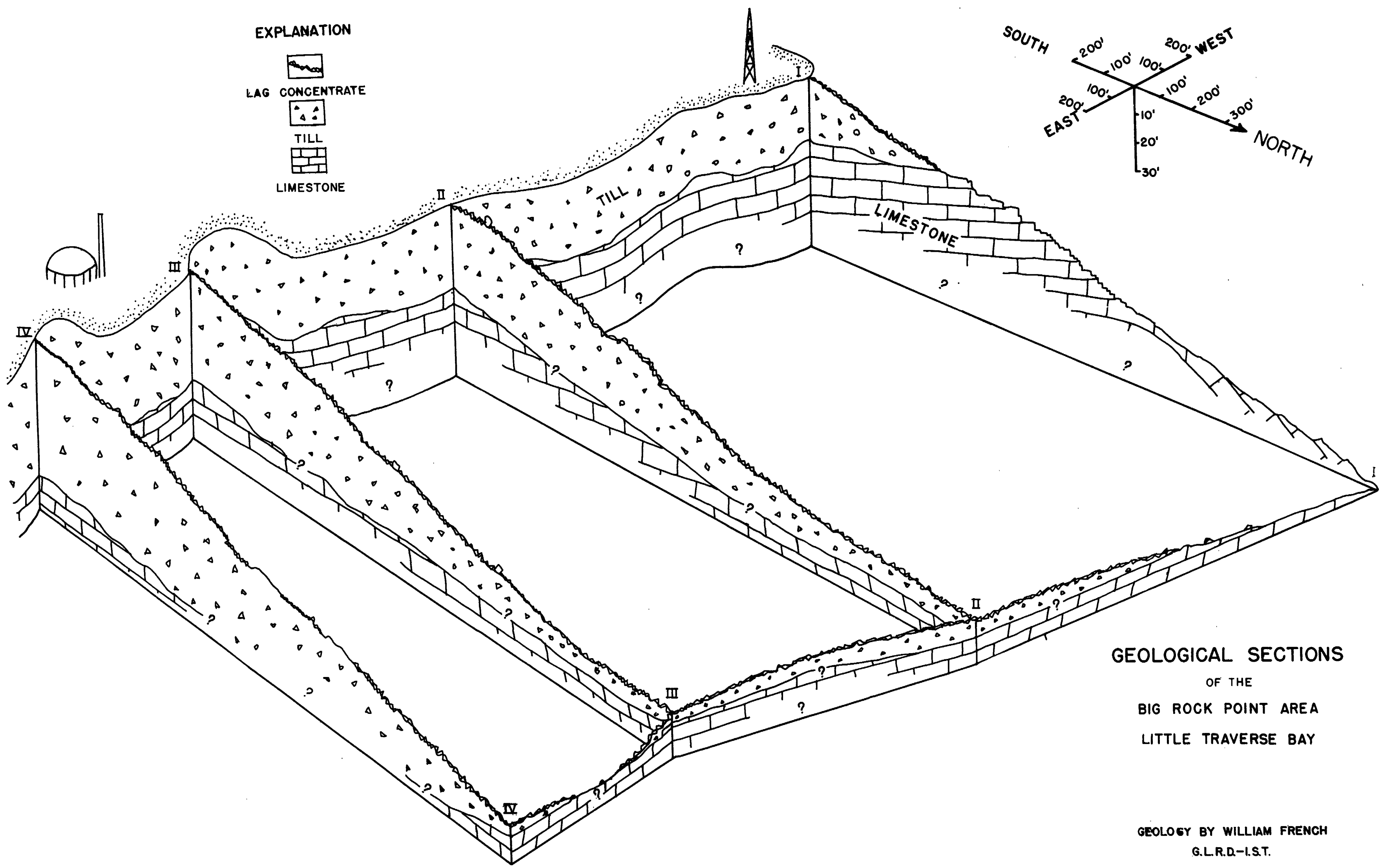

Fig. 2. Geological sections of the Big Rock Point area of Little Traverse Bay.

The bedrock found outcropping offshore is chiefly a light brown, hard limestone with a few small layers of softer grey limestone. This has been tentatively placed in either the Charlevoix stage of the Petoskey limestone or the Gravel Point stage of the Alpena limestone.

The geological section of line I depicts the limestone as undergoing a reversal of dip and tending to dip lakeward at the outer end of the line. This is inferred from topography but is supported by other evidence from the regional topography which shows that the structure of the bedrock in the region is irregular. This may be due to solution, slumpage, and recementation of the underlying strata in the past. The dips shown on the cross sections are, of course, exaggerated and are in reality only one to two degrees. The depth-to-bedrock in the outer portions of lines II, III, and IV, is inferred and is based on topographic indications, from an additional fathogram, that beyond the end of line III the bedrock outcrops at a depth of 50 feet. The depth-to-bedrock shown at the inner ends of lines III and IV is based on the test borings made at the reactor site (Zumberge, 1960).

Except for the outcrop area off Big Rock Point, the bedrock in the entire area is covered by a layer of reddish-brown glacial till. This till has been identified as belonging to the Valders stage of the Wisconsin glaciation and is typically a hard, sandy clay containing pebbles, cobbles, and boulders.

Wave erosion of the till surface has removed the clay and sand leaving the pebbles, cobbles, and boulders to form a lag concentrate. This is the source of the boulder pavement which covers the lake bottom. This surficial deposit is not very thick. Experimental excavation near the reactor area reached till about two feet below the bottom. In two places along line IV current and/or ice erosion has removed the lag concentrate cover, leaving bare till which shows scour effects indicative of at least periodic rapid bottom currents.

IV. BAY CIRCULATION UNDER PREVAILING WINDS

One objective of the field operations during the summer of 1960 was the measurement of surface currents under prevailing winds over as much of Little Traverse Bay as possible. This was to be in addition to, and subsidiary to, detailed observations of currents under various wind regimens in the immediate vicinity of the plant site. This objective was partially attained, but a cessation of winds from westerly quarters during the latter half of August precluded as complete a coverage of the bay as had been anticipated. The circulation pattern of the bay (Fig. 3) has been deduced from the available data. In Fig. 3, those parts of the pattern which are uncertain are indicated by dashed arrows.

Measurements of surface currents were by "current poles" and "current drogues." Each current pole consisted of a four-foot length of fir 2 x 4, ballasted at one end with two bricks, so that it floated in a vertical position. The top six or eight inches protruded above the surface of the water, and bore a small, bright orange pennant.

Each current drogue consisted of a truncate cone of 26-gauge galvanized sheet metal, 30 inches in height, 36 inches in diameter at the large end, and 32 inches at the small end. Both ends were open, so that the structure resembled a bottomless washtub. The small end of the drogue was attached to a float consisting of a pair of gallon glass jugs bearing an orange pennant atop a bamboo flagstaff five feet long; the jugs floated in almost submerged position and exposed only a small surface area to the wind. All poles and drogues bore identifying numbers or letters. Under operating condition, poles and drogues were released in series, as many as fifteen being used during a given operation.

Although the drogues exhibited slightly less response to the direct effect of wind than did the poles, repeated comparisons indicated that the windage exhibited by the poles did not result in a velocity or path of travel significantly different from that of the drogues. Both were used throughout the entire survey, so that continual cross-checks could be made. In 26 pairs of comparisons the current poles moved on the average 3% faster than did dye patches. The drogues averaged about 1.5% faster than dye in the same number of comparisons.

The point of release of pole or drogue was ascertained by sextant fix to landmarks on shore. The time of release was recorded, as well as the local wind velocity and direction. During any day's operations, poles and drogues were left in the water for a number of hours, during which period each was located by sextant fix several times. Plotting of these fixes allowed reconstruction of the paths of travel, and distance traveled in elapsed time between fixes gave a measure of speed of progress.

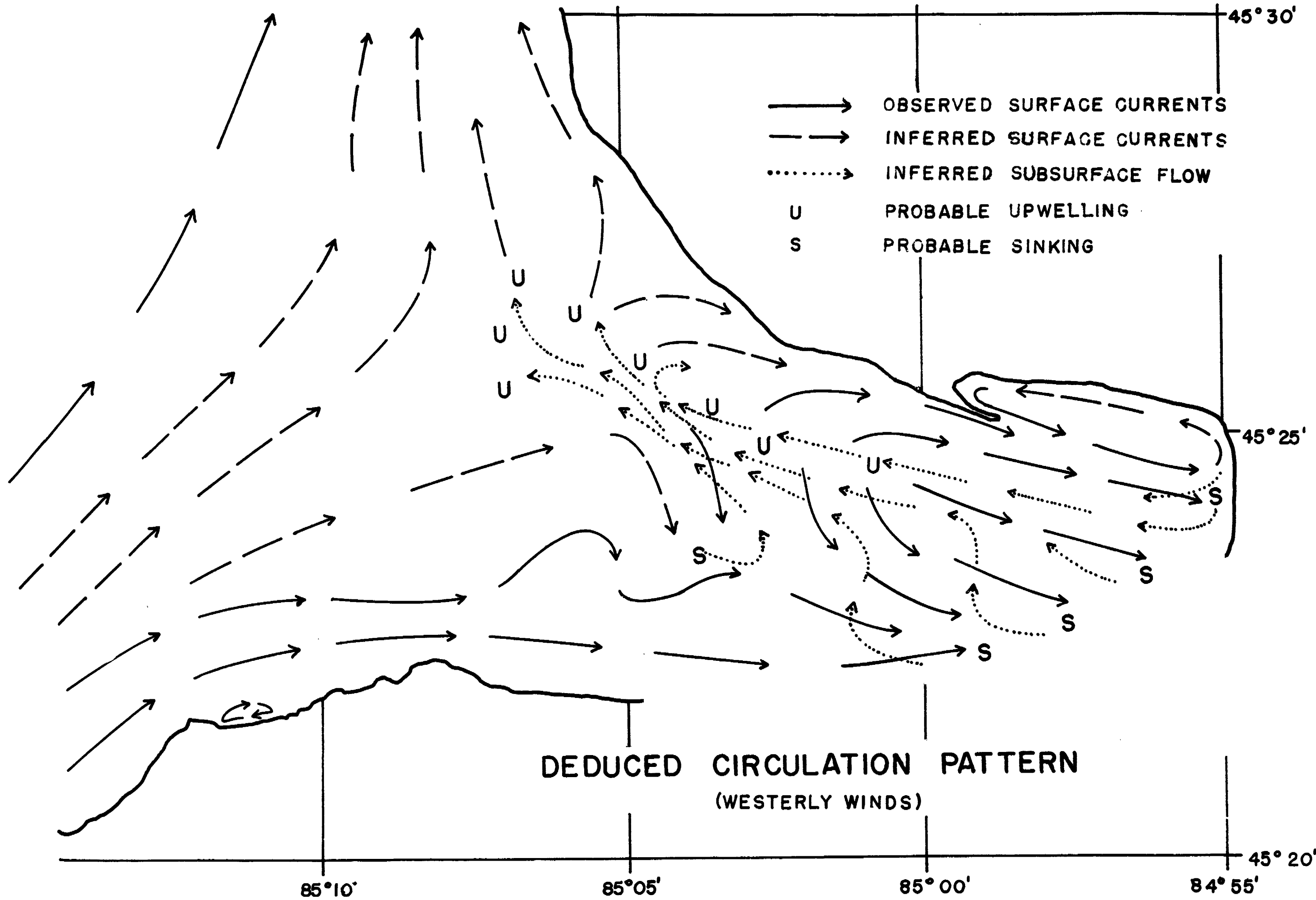

Fig. 3. Deduced circulation pattern of Little Traverse Bay under westerly winds.

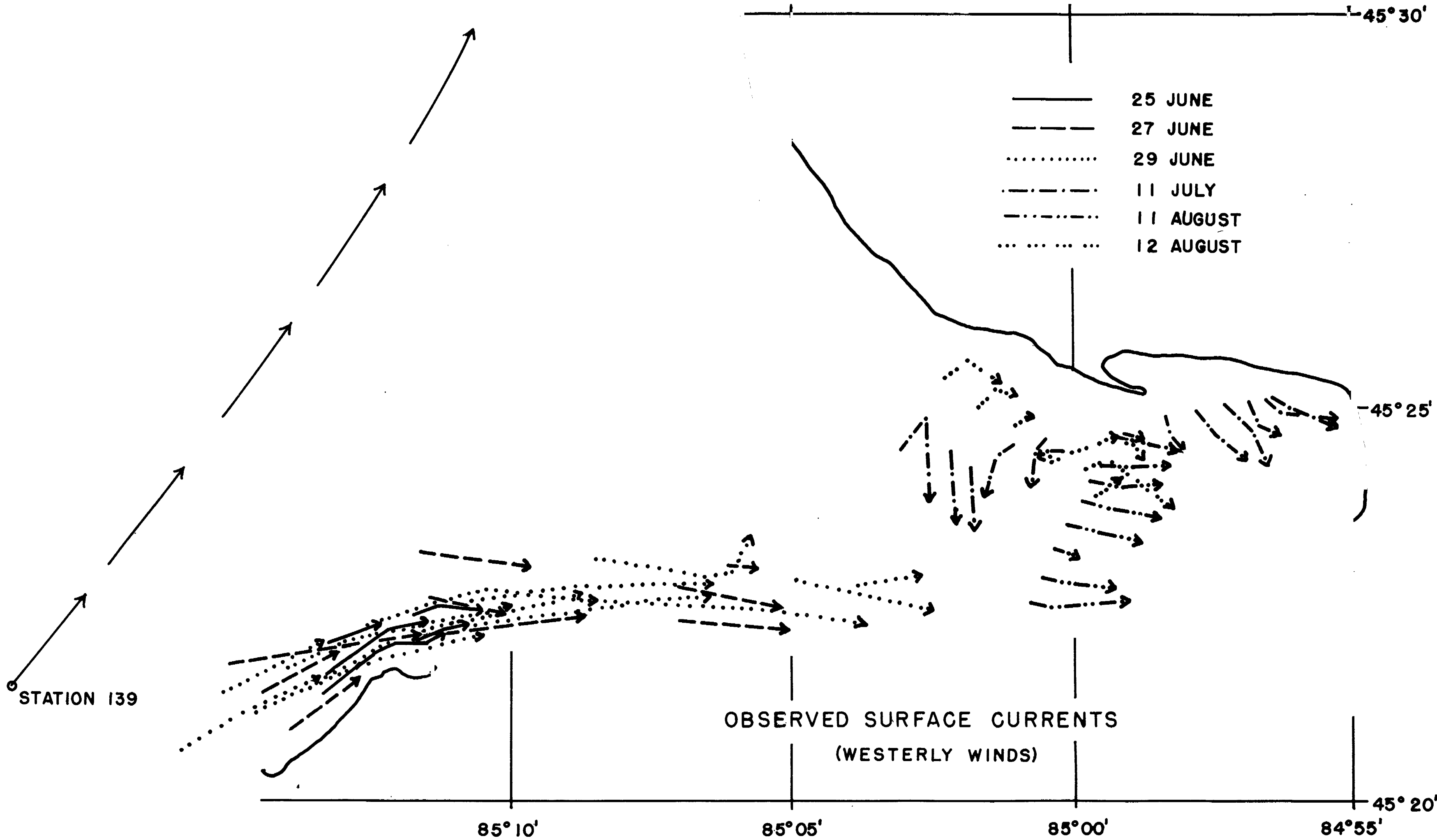

Fig. 4. Observations of surface currents made under westerly winds.

Eight sets of observations were obtained on winds essentially from a westerly direction. They are summarized in Table I and shown in Fig. 4.

TABLE I

CURRENT OBSERVATIONS UNDER WESTERLY WINDS

Date	Wind		Current		Location
	Direction From	Velocity (mph)	Direction Toward	Velocity (mph)(avg)	
25 June	W	8-12	NE	0.34	Off Big Rock Point.
27 June	SW	8-10	NE-E	0.40	Between Point McSauba and Penn-Dixie.
	W	15-20			Between Point McSauba and Penn-Dixie.
29 June	W	8-12	NE-E	0.72	Between Point McSauba and Penn-Dixie.
11 July	WSW	8-12	S	0.30	Along lat. 45°25' between Forest Beach and west end of Harbor Point.
	WSW-WNW	8-12	SE	0.22	Along lat. 45°25' between east end of Harbor Point and inner end of bay.
11 Aug	W	15-20	E	0.35	Between Penn-Dixie and Harbor Point.
12 Aug	W	6-15	NE-E	0.16	1/2 mile offshore between Forest Beach and west end of Harbor Point.
	W	6-15	NE-SE	0.35	North-central portion of bay off Harbor Point.

All drogues, poles, and dye patches released in the main south-shore current between Point McSauba and the Penn-Dixie plant moved essentially parallel to shore and toward the head of the bay. In no case was movement in the opposite direction found under westerly winds. Between Nine Mile Point and the cement plant there was some offshore movement of drogues.

Of the releases made on 11 July, those west of Harbor Point moved essentially to the south while those from the point eastward moved east or southeast toward the inner end of the bay (see Fig. 4).

On 11 August, the drogues and poles released between the cement plant and Harbor Point all moved east, toward the head of the bay.

On 12 August, the westernmost three drogues and poles (released off Forest Beach) were set closer to shore than those of 11 July; they first moved northeast toward shore, and then turned southeastward toward the tip of Harbor Point after reaching the four-fathom contour. The remaining two, set near the center of the bay south of Harbor Point, moved toward the head of the bay.

In addition to the observations described above, the movements of drift bottles released by Ayers et al. (1958) at their Station 139 three and one-half miles northwest of Charlevoix under west and southwest winds have been incorporated into the present analysis.

Movement of water from the southwest resulted in an eastward current along the south shore, extending to the inner end of the bay. This was consistently shown by pole, drogue, and dye movements. The drift-bottle data of Ayers et al. (op. cit.) indicate that, from a station three and one-half miles off Charlevoix, the northeast current did not enter the bay. All ten drift bottles released there on 28 and 29 June, 1955, passed to the Straits area, even though winds were from the southwest on the 28th and west on the 29th. It appears that the principal inflow into Little Traverse Bay is a narrow coastal flow, not over three miles in width, coming from the direction of Grand Traverse Bay to the southwest.

As previously mentioned, the current along the south shore extended to the inner end of the bay. Furthermore, the eastward movement of eight poles and drogues set on a line between the cement plant and Harbor Point, on 11 August, indicated that from this line to the head of the bay all surface flow was essentially to the east. West of this line, five drogues and poles released to the southwest of Harbor Point, on 11 July, moved in paths indicative of a flow to the south, which was apparently incorporated into the eastward current along the south shore. Three poles and drogues released on 12 August to the west of Harbor Point, off Forest Beach, did not move south, but instead went northeast to the vicinity of the four-fathom depth contour, and thence east toward the tip of Harbor Point. This alongshore movement, when considered in conjunction with the southward movement found on 11 July, is taken to indicate a divergence located about one and one-half miles off Forest Beach.

Water passing from this divergence past Harbor Point could either have been incorporated into the flattened counterclockwise eddy believed to lie along the north shore east of Harbor Point, or have been carried directly to the head of the bay.

No evidence of surface movement out of the bay was obtained in the areas covered. The consistency of movements toward the head of the bay indicate strongly that there must be subsurface return flow from that region to the divergence off Forest Beach, if not further.

The divergence off Forest Beach was located in a position where at least partial upwelling of lakeward moving deep water could occur. Here the 175-foot deep inner basin of the bay becomes greatly constricted by the northeastward sill protruding from Nine Mile Point. The obstruction formed by the sill and the converging slope from the north shore could force an upwelling of water, of which part could enter the eastward alongshore current toward Harbor Point and part the mid-bay southward surface current emanating from the divergence. Since this upwelled water would not actually represent an escapement from the bay, there must be a continued lakeward movement of the deep water, probably along the extension of the 175-foot basin.

Water passing to the northeast three and one-half miles off Charlevoix did not enter the bay; on the other hand, a coastal flow closer to shore did enter. It appears that a divergence other than that described for the Forest Beach region exists in the outer end of the bay. Since none of the drift bottles from the station off Charlevoix stranded south of Waugoshance Point, this divergence must be well out in the bay mouth. It has been estimated to lie off Seven Mile Point. Configuration of the bottom topography substantiates this location; the north-south ridge north of Big Rock Point rises to 100 feet and is in excellent position to divide the flow from the southwest. Drogues set at 100 feet on 12 August showed that currents at that depth were in essentially the same direction as those at the surface. It is logical, then, to expect that the 100-foot apex of the ridge might divide the current from the southwest and produce an upwelling behind the ridge and off Seven Mile Point. Upward movement of water in this upwelling would function as a negative pressure which would couple with the positive pressure generated in the head of the bay by currents moving onto land there. The pressure-couple and the orientation of the bay's deep inner basin are well suited to the production of subsurface movement of water from the head of the bay to the upwelling off Seven Mile Point, and the constriction of the deep inner basin is in proper position to provide a partial upwelling in the region off Forest Beach. Water upwelled off Seven Mile Point and moving to the northwest appears to be the only surface escapement of water from the bay.

V. CURRENTS IN THE VICINITY OF THE PLANT

A primary part of the field operations was the observation, under as many different wind directions as possible, of surface currents in the vicinity of the plant. It was particularly desired to determine the manner in which the currents are controlled by wind, to permit reasonably accurate forecasting of the direction of flow of water passing the site.

Surface currents were measured by observing the movements of current poles and drogues as described in the treatment of the general circulation of Little Traverse Bay. Movements of dye patches used in dilution studies contributed additional information, particularly close to shore in the embayment contiguous with the east side of Big Rock Point, where the effluent channel from the condensers enters the bay.

A. THE ALONGSHORE CURRENTS AND THE BIG ROCK EDDY

Wind and current measurements in the vicinity of the plant are summarized chronologically in Table II. Studies were made on 15 days, between 25 June and 24 August, when winds were sufficiently steady to permit observations under a given wind over a period of several hours. Data were collected during winds from N, NNE, ENE, E, S, SW, WSW, W, WNW, NW, NNW. The lack of data for winds from the NE, between ESE and SSE, and SSW is due to absence of winds from those directions during our operations.

In Table III, observations of wind and current have been arranged according to wind directions, beginning with north and proceeding clockwise around the compass to NNW. One section of this table contains those observations made to lakeward of the small embayment contained between Big Rock Point and the point at the highway park 1-1/4 miles east; the other contains those made within that embayment. The separation has been made because currents within the embayment frequently differed from those outside during the same period of observation, under the same winds.

The orientation of the shoreline at the plant site is approximately ExN - WxS, based on a line tangent to Big Rock and Nine Mile Points. When the wind was in the quadrant N to E, the main current off the plant site, lakeward of the small embayment, ran parallel to the shore toward the WxS (out of the bay). When the wind was from WNW, NW, or NNW, this current ran approximately to the WSW, still directed out of the bay but possessing an onshore component. West of Big Rock Point the orientation of the shoreline changes, sloping to the southwest. Under all observed winds except east winds, the out-of-the-bay current passing the plant turned approximately southwest and followed the shore. On east winds, the current diverged from the shore after

TABLE II

CHRONOLOGICAL OBSERVATIONS OF WIND AND CURRENT
IN THE VICINITY OF THE PLANT SITE

Date	Location	Wind		Current	
		Direction From	Velocity (mph)	Direction Toward	Velocity (mph)
25 June	1/8 - 1 mi off plant	W	8-12	ExN	0.34
27 June	5/8 mi off plant	WSW	5-10	ExN	0.40
29 June	3/8 - 1 mi off plant	WSW	8-12	ExN	0.72
13 July	1/2 - 1 mi off plant	NNE	20-24	WxS	0.45
21 July	1/4 - 1 mi off plant	S	8-12	NExE	0.46
25 July	0 - 1/4 mi off plant	S	1-3	NNE	0.20
29 July	0 - 1/8 mi off plant	SW	8-12	NWxN	0.32
	1/4 mi off plant	SW	8-12	ExN	0.39
4 Aug	3/8 - 1-5/8 mi off plant	N	4-7	SW	0.58
	0 - 1/16 mi off plant	WNW	2	ExN	0.27
	1/4 mi off plant	WNW	2	WSW	0.68
9 Aug	5/16 - 1-3/8 mi off plant	E	10	W	0.46
10 Aug	1/8 mi offshore, 7/16 mi E of plant	NW	8-9	ExN	0.53
	1/4 - 1/2 mi off plant	NW	8-9	SWxW	0.32
15 Aug	3/16 mi off plant	NNW	10-12	WxS	0.09
19 Aug	1/4 mi off park	ENE	4-6	WxS	0.29
24 Aug	1/8 mi off plant	ENE	8-12	SW	0.36
	1/4 - 1-1/4 mi off plant	ENE	8-12	WSW	0.65

TABLE III

WIND AND CURRENT DIRECTIONS OUTSIDE AND INSIDE
THE BIG ROCK EMBAYMENT

Outside Bay		Inside Bay	
Wind From	Current Toward	Wind From	Current Toward
N	SW	N	E
NNE	WxS		
NE			
ENE	WSW	ENE	SW*
	WxS		
E	W		
ESE			
SE			
SSE			
S	NExE	S	NNE
SSW			
SW	ExN	SW	NWxN
WSW	ExN		
	ExN		
W	ExN	W	E
WNW	WSW	WNW	ExN
NW	SWxW	NW	ExN
NNW	WxS		

*Appeared to be recurving into eddy.

passing to the westward of Big Rock Point, and continued in a nearly westerly direction.

When the wind was in the quadrant S to W, inclusive, the current was directed into Little Traverse Bay: SW, WSW, and W winds set up eastward currents parallel to shore; S winds resulted in a current which, while being directed into the bay, moved offshore toward the northeast.

In the small embayment between Big Rock Point and the highway park, current directions differing from those to lakeward indicated the presence of an elongate eddy extending from Big Rock to the park. This eddy appeared to reach to lakeward about as far as the line tangent to Big Rock and Nine Mile Points. The observed currents evidencing the existence of this eddy appear in Table III.

The oppositely directed currents within and without the embayment are definite indications of the presence of a small, flattened eddy; the lakeward side ran in the same direction as did the main current outside the embayment,

while the shoreward side necessarily ran in the opposite direction in completing the rotation. On two occasions, under winds from the west and from the south, the eddy was not found. During the west wind, all currents, both inside and outside the embayment, were to the eastward. On the south wind, current outside the embayment was to the NExN, and inside the embayment, NNE. It would not be expected, however, that a south wind would generate an eddy, all transport at this time being directed offshore. The situation observed for the west wind was the only occasion when the eddy did not appear to be operating. There is no reason to believe that it should not operate under a west wind, and its apparent absence on that occasion cannot be explained. Unfortunately, cessation of westerly winds gave no further opportunities to search for it under west-wind conditions. It is likely that it exists most of the time when eastward currents exist. When the wind is such that the currents run essentially away from the shore, it would not be expected that the eddy would be present.

The eddy is not considered to be an important part of the currents in the region of the reactor. It is small and weakly moving; it may be either destroyed or severely modified when the plant cooling-water discharge begins.

B. WIND CONTROL OF CURRENTS

The surface currents in the region of the plant originate from the interaction of wind-stress energy input, the rotation of the earth, and local physical or hydrodynamic barriers. The available evidence indicates that a wind of a one to two hours' duration is sufficient to alter an existing current regime.

In considering the manner in which the currents are controlled by the winds, the effect of the rotation of the earth (Coriolis force) must be taken into account. Over the open lake, wind-driven water does not move directly downwind but at an angle to the right of the wind direction. In mid-latitudes, this angle is usually of the order of 45°. Observed currents, however, are frequently found to move in downwind directions other than this 45° deviation. Such behavior is caused by some barrier which impedes the progress of the water initially set in motion by the wind (called the primary transport). Impingement of primary-transport water against the barrier, which may be the shore or another current, results in secondary currents. Secondary current tends to run parallel to the axis of the barrier against which the primary transport has impinged, the direction of flow being determined by the angle at which primary transport encounters the barrier.

The direction of the shoreline at the reactor is essentially ExN - WxS. Currents measured during WNW, NW, NNW, N, NNE, ENE, and E winds were directed westward out of the bay, while those measured during S, SW, WSW, and W winds were directed eastward into the bay. If the initial movement of water is taken to be 45° to the right of the wind direction, the primary transport during observed winds WNW through E (current moving out of the bay) would be as follows:

WNW: 45° primary transport toward shore, approximately normal to shore.
NW through NNE: 45° primary transport toward shore but angled to S - WSW.
ENE and E: 45° primary transport away from shore, angled to WNW and NW.

The primary water transports resulting from NW through NNE winds encounter the barrier formed by the shoreline at less than critical angle and set-up does not occur, the westward secondary current merely sliding along the shore. Winds from the WNW, however, direct water onto the shore at an angle which is nearly normal to the shoreline. On the single occasion when currents were observed under WNW winds, the current was moving out of the bay; it seems probable (discussed below) that currents are likely to be variable under WNW winds, and may be found moving either into or out of the bay.

The primary transports occurring under ENE and E winds would move away from shore, which under these winds does not function as a barrier. However, currents measured during these winds were found to move in a W, WxS, or WSW direction, rather than to the WNW and NW, indicating that secondary currents were also present when these winds were effective. Ayers et al. (1958) found that winds from northeasterly directions tended to create a southward current along the east side of Lake Michigan which passed across the mouth of Little Traverse Bay. The margin of this current probably functions as a barrier against which set-up can occur; this would account for secondary W to WSW currents found under ENE and E winds.

Considering next those winds during which currents were found moving into Little Traverse Bay, the primary transport would be as follows for winds S through W:

S: 45° primary transport away from shore, angled to NE.
SW, WSW, W: 45° primary transport toward shore, angled to E - SE.

In the case of the S wind, the observed current nearly coincided with the theoretical 45° transport, indicating a lack of offshore set-up and a probable absence of secondary currents in the southern half of the bay. On SW, WSW, and W winds, however, the primary transport would be directed onto shore, at an angle of incidence resulting in set-up against shore and a secondary current directed into the bay. When set-up occurs, the secondary current flows geostrophically on the slope of the set-up and in such a direction that the high side of the set-up is on the right-hand side of the current.

Since the observed currents can be satisfactorily explained on the basis of 45° primary transport and secondary currents, it appears possible to predict current directions off the plant for wind from all directions. Winds from NW around to E generated currents out of the bay; winds from S around to W generated currents into the bay. No observations were obtained during winds from NE, ESE, SE, SSE, or SSW. Probable currents existing under these winds can be predicted, however, on the assumption that primary transport will be

45° or nearly so, and that secondary currents will flow along known or logically-suspected barriers. Under these conditions, NE winds would generate an initial movement to the west, which would likely encounter and be entrained by the southward flow at the mouth of the bay described by Ayers _et al_. (_op_. _cit_.). Winds from ESE would initiate a primary transport to the NNW; there are not sufficient data to ascertain the probable fate of this drift. SE winds would transport water almost directly away from shore, and SSE winds would move it offshore and angled slightly into the bay, with no secondary effects becoming noticeable near the south shore. Since W winds were seen to direct the surface current into the bay, and NW winds direct it out of the bay, winds between W and NW constitute a transition phase, with a shift across this section resulting in a change of about 180° in current direction. Currents under WNW winds, then, would tend to be variable and unpredictable. Similarly, observations showed that E winds generated currents running to the west (out of the bay), while S winds moved water into the bay. A transition phase must also exist between E and S, and although it was not observed, it probably occurs at about SE, where transport is nearly normal to shore. ESE winds should initiate a primary transport out of the bay, and SSE or SSW winds a transport into the bay.

To summarize, water discharged from the plant would enter directly into the small eddy immediately adjacent to the plant, when conditions were such that the eddy would be operative. The eddy in turn feeds into the main alongshore current which would most probably be as follows under the various winds:

Wind From	Current
NW, NNW, N, NNE, NE, ENE, E	Out of the bay.
ESE	Out of the bay.
SE	Transition phase.
SSE, S, SSW	Into the bay.
SW, WSW, W	Into the bay.
WNW	Transition phase.

C. RELATIONSHIP OF CURRENT VELOCITY TO WIND VELOCITY

Current velocity in lakes is usually considered to be about 2% of the causative wind's velocity. Velocities of the alongshore currents of Little Traverse Bay, however, show a bi-modal relationship to wind velocity; one mode appears to be at about 2% and the other at about 6% of wind velocity (Fig. 5).

Analysis of this situation reveals that the two relationships are dependent upon the previous day's wind direction. When the winds of the observation day _and_ of the preceding day are from the same direction, the current moves at about 2% of velocity of the observation-day wind. When wind of the preceding day has been generally opposite to wind of the observation day, the latter's current moves at about 6% of observation day wind velocity. Higher current

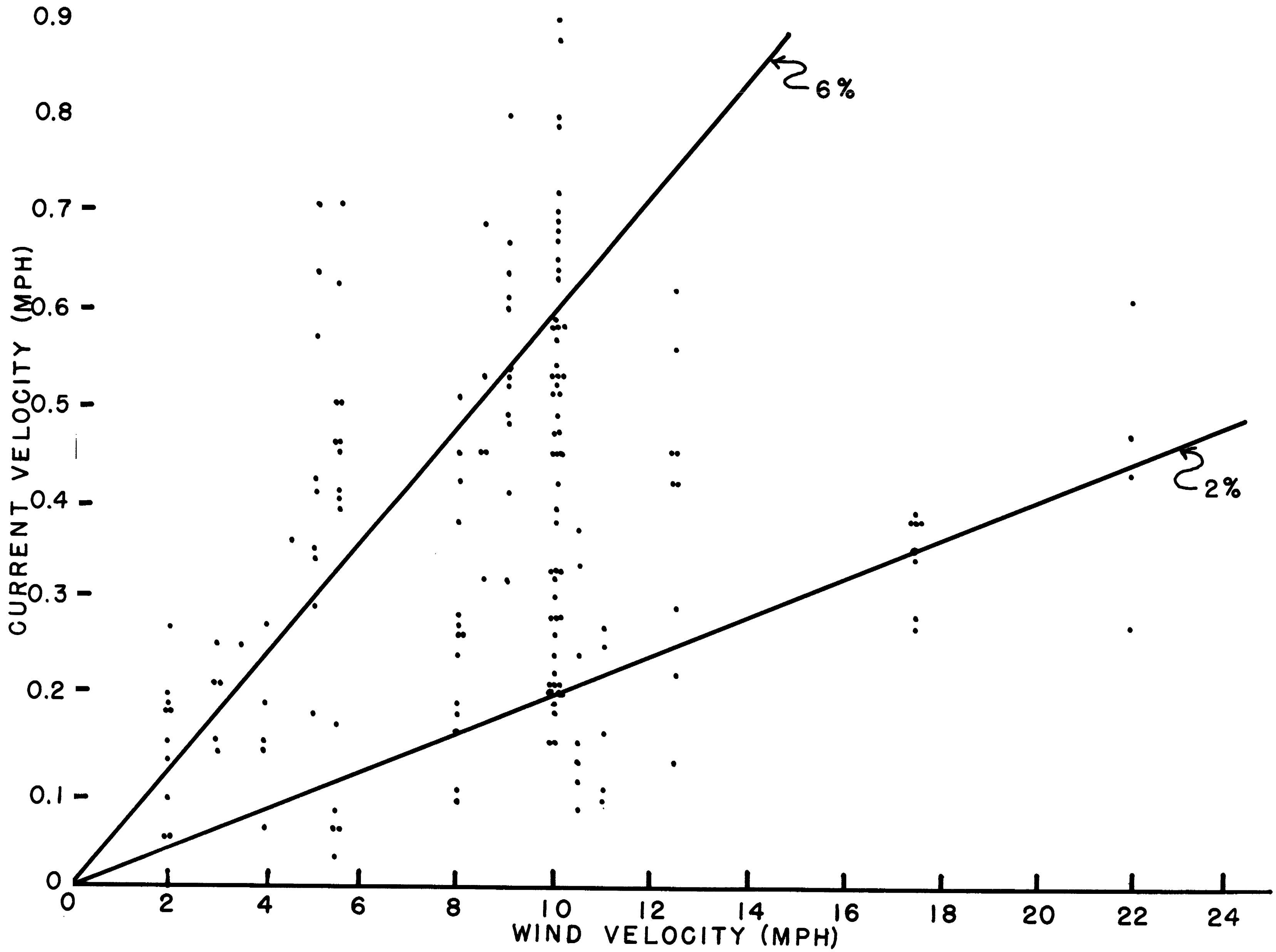

Fig. 5. Relationship of current velocity to wind velocity.

velocities in a new current after a wind change are believed to be a result of the increased efficiency of wind-stress energy input accompanying the higher choppier seas that run during the period when new wind is opposing old current.

VI. DILUTION STUDIES

The work carried out in this phase of the program was designed to give measures of the natural rates of dilution in the surface waters of Little Traverse Bay. Dilution is the result of mixing processes in the water under conditions of turbulent flow and of eddy diffusion (as opposed to the more simple laminar flow and molecular diffusion). The data show that the diminution of concentration of a tracer dye introduced into the bay water may, during the first hour after introduction, be adequately described as a simple geometric dilution process. After the first hour, however, the dye shows a diminishing curvilinear rate of decrease.

A. METHODS

The dilution studies were made with the fluorescent dye, Rhodamine B, and an ultraviolet fluorometer. The fluorometer was calibrated frequently against known-concentration dilutions of Rhodamine B in Lake Michigan water. The fluorometer compared the fluorescence under ultraviolet of a vertical tube of dyed water with that of a similar tube of undyed Lake Michigan water. A pump attached to the outlet of the instrument allowed the pumpage of dyed water without the generation of bubbles in the dyed-water tube. As used, the fluorometer was capable of measuring dye concentrations of one part per billion (weight of dry dye in water).

A fluorescent dye solution (with specific gravity adjusted to compare with the warmed reactor effluent) was introduced into the bay water, and the dye concentration was monitored by fluorometer to obtain the time rate of dye concentration decrease. The fluorescent dye was one pint of a stock solution of Rhodamine B in 40% acetic acid solution, mixed with three quarts of methanol. This dye solution would float in the upper layer of water, corresponding to the expected behavior of the warmed reactor effluent. All the dye stayed in the upper 10 feet of the water, with the majority of it less than 3 feet from the surface.

After the dye was introduced, the research vessel was slowly coasted through the resultant dye patch while dyed water was continuously pumped through the fluorometer. Successive passes through the dye were made, and the maximum observed concentration recorded on each pass. By recording the concentration maxima, a minimum rate of dilution is obtained (dilution of the dye-patch center was largely a matter of dye being diluted with dyed water). A typical sequence consisted of passes through the densest part of the dye patch every ten or twenty minutes until the dye patch became too diffuse to measure accurately.

The passage of the boat through the dye patch was, so far as visual observation could determine, not a source of significant artificial turbulence. Moving at a fraction of a mile per hour, with power off and the propeller still, the boat passed through the patch with apparent laminar flow along the hull and only small gentle eddies behind the stern.

B. THEORETICAL CONSIDERATIONS

Considering the dye concentration as a function of time C(T) given in the manner

$$C(T) = C_o\, f(T) \qquad (1)$$

where C(T) is maximum concentration observed in the dye patch at time T, and C_o is the initial concentration. We may define the dilution as

$$D(T) = C_o/C(T) = 1/f(T) \qquad (2)$$

From relation 2 it is evident that the determination of the maximum values of the dye concentration [considered to be C(T)] will give minimum values for the dilution D(T). Figures 6, 7, and 8 show representative dilution curves obtained during the series of dilution measurements.

From the curves, it is seen that the dilution obeys the relation

$$\log D(T) = aT = -\log f(T) \qquad (3)$$

where a may be constant or decreased and is interpreted as

$$a = \frac{1}{t}\log r_t \qquad (4)$$

Equation (1) may therefore be written as

$$C(T) = C_o r_t^{-(T/t)} \qquad (5)$$

In the above expressions, t specifies the dilution period (i.e., r_t denotes a dilution by a factor r in a period of t minutes).

Let us now consider the mechanics of the dilution process to determine the significance of r_t. The total amount of dye in the dye patch being a constant, if we assume a uniform concentration through the patch, the product of the dye concentration, C, and the total volume of the dye solution, V, is a constant

$$CV = B$$

Considering the dilution to proceed at a constant rate, the expression for the volume of the dye patch becomes a geometric series in time and may be written

$$V(T) = V_o \, r_t^{(T/t)} \qquad (7)$$

where V_o is the initial volume of the dye patch, and r_t is the dilution ratio. Substituting Eq. (7) into Eq. (6), the expression for the dye concentration as a function of time becomes

$$\begin{aligned} C(T) &= (B/V_o) \, r_t^{-(T/t)} \\ &= C_o \, r_t^{-(T/t)} \end{aligned} \qquad (8)$$

This is the same expression as that obtained from the dilution measurements [Eq. (5)] and demonstrates that we may consider the dilution to proceed as a simple geometrical process.

The assumption of uniform dye concentration, used in writing Eq. (6), is closest to real conditions when the uniform concentration considered is the mean concentration. In our practice, however, the concentration used is the maximum, and the dilution ratios that result are conservative.

C. RESULTS

A total of 34 dye experiments were carried out under westerly winds (current running into the bay) and under easterly winds (current out of the bay). Twenty-two of these extended to an hour or more. Each experiment consisted of a single dye introduction which was not recharged. No difference was observed in the behaviors of dye patches moving into or out of the bay; they are, consequently, not kept separate in sections to follow.

Of the 22 dye patches that were followed for an hour or more, only six exhibited a true geometric dilution which yielded straight lines on a semi-log plot. A typical four of these are presented in Fig. 6. Of the remaining 16, eight showed pronounced tendencies toward abrupt decrease in dilution rate after the initial 12 to 40 minutes; six of these are presented in Fig. 7. The remaining eight exhibited diminishing dilution rates of the types shown in Fig. 7 but the changes were less pronounced.

Fig. 8 is a plot of the envelope that contained the observations, and the computed trend-line of diminishing dilution ratios around which the observations were distributed. The computation of this line is described under "Discussion" below.

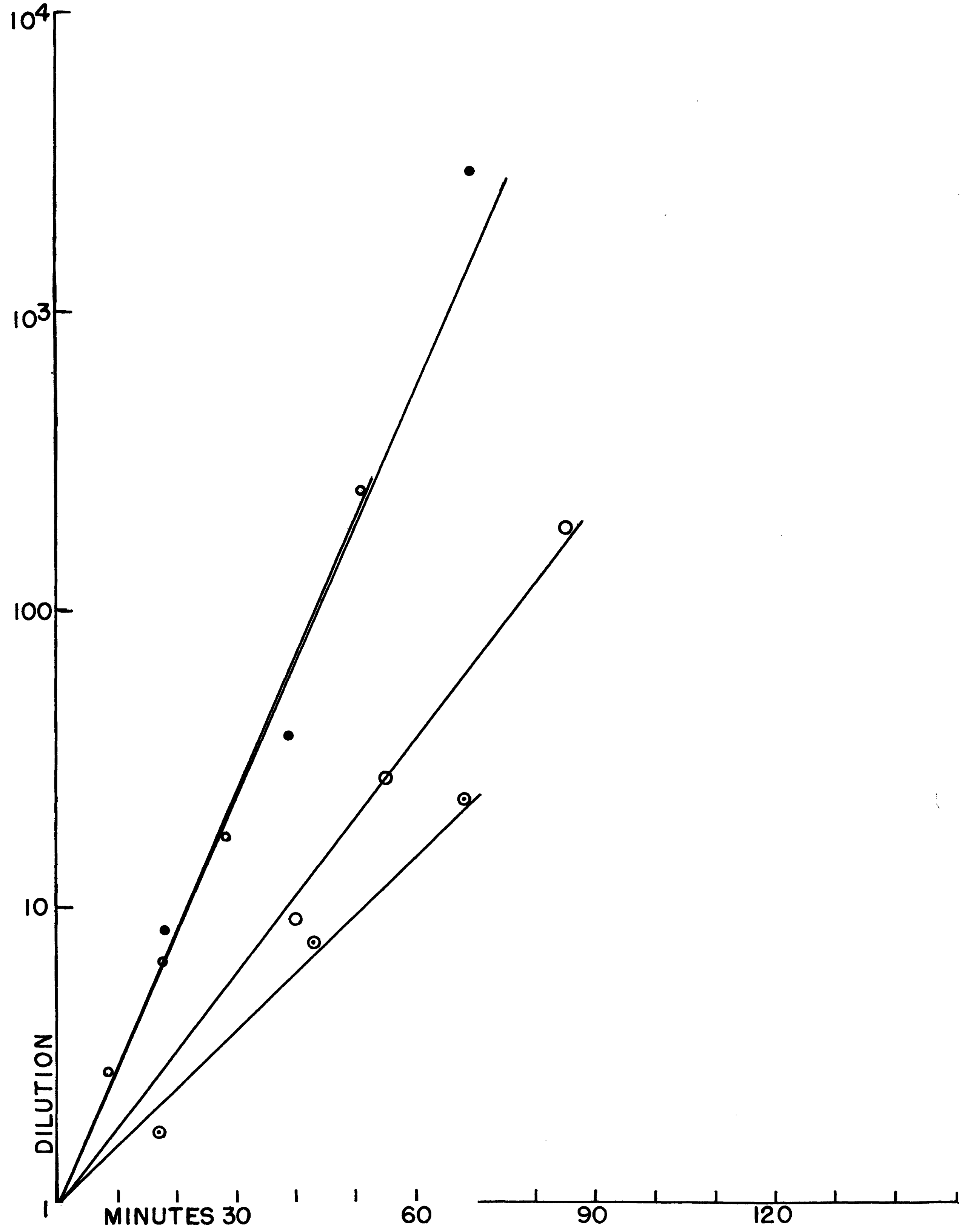

Fig. 6. Representative dilution curves: geometric dilutions.

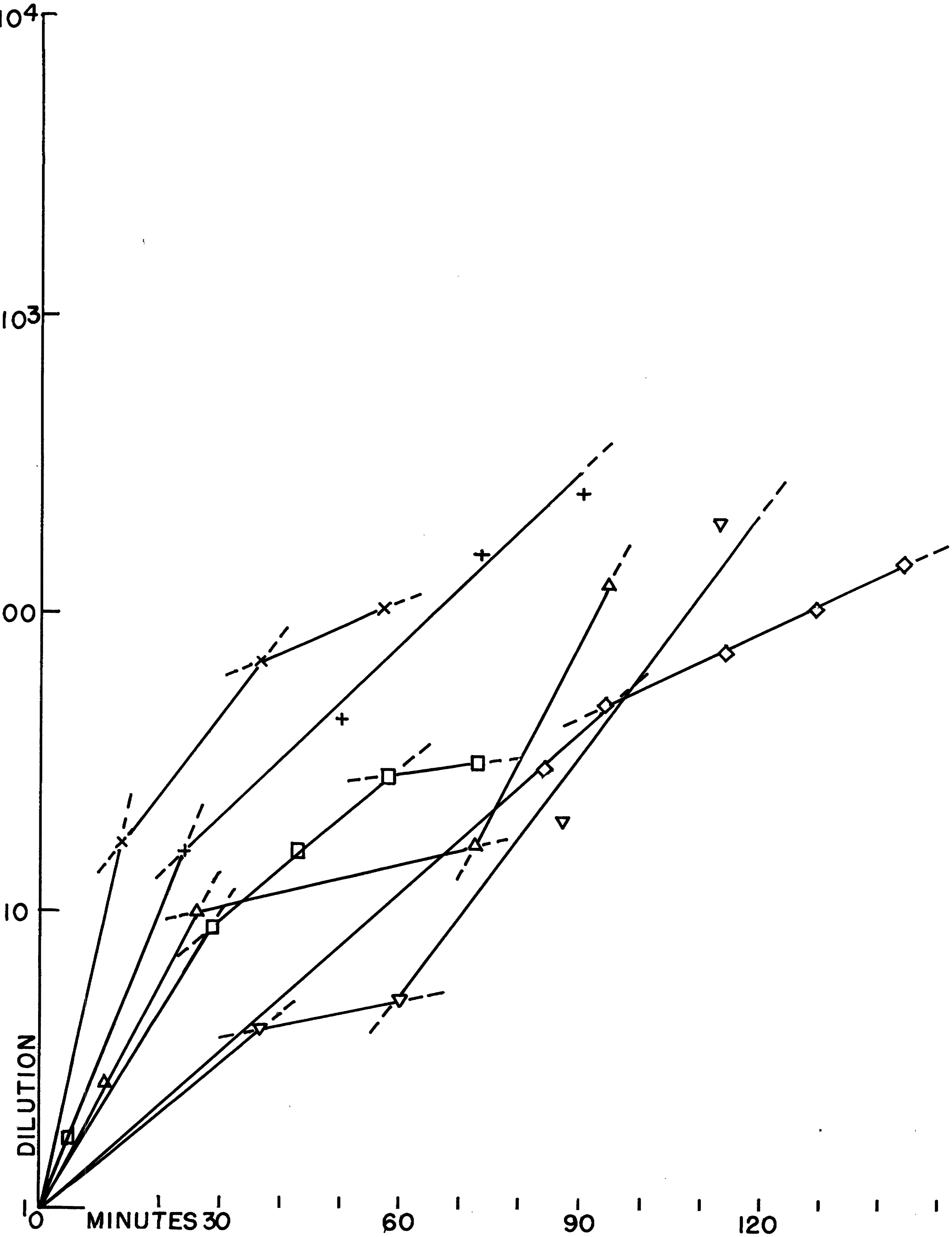

Fig. 7. Representative dilution curves: decreasing dilutions.

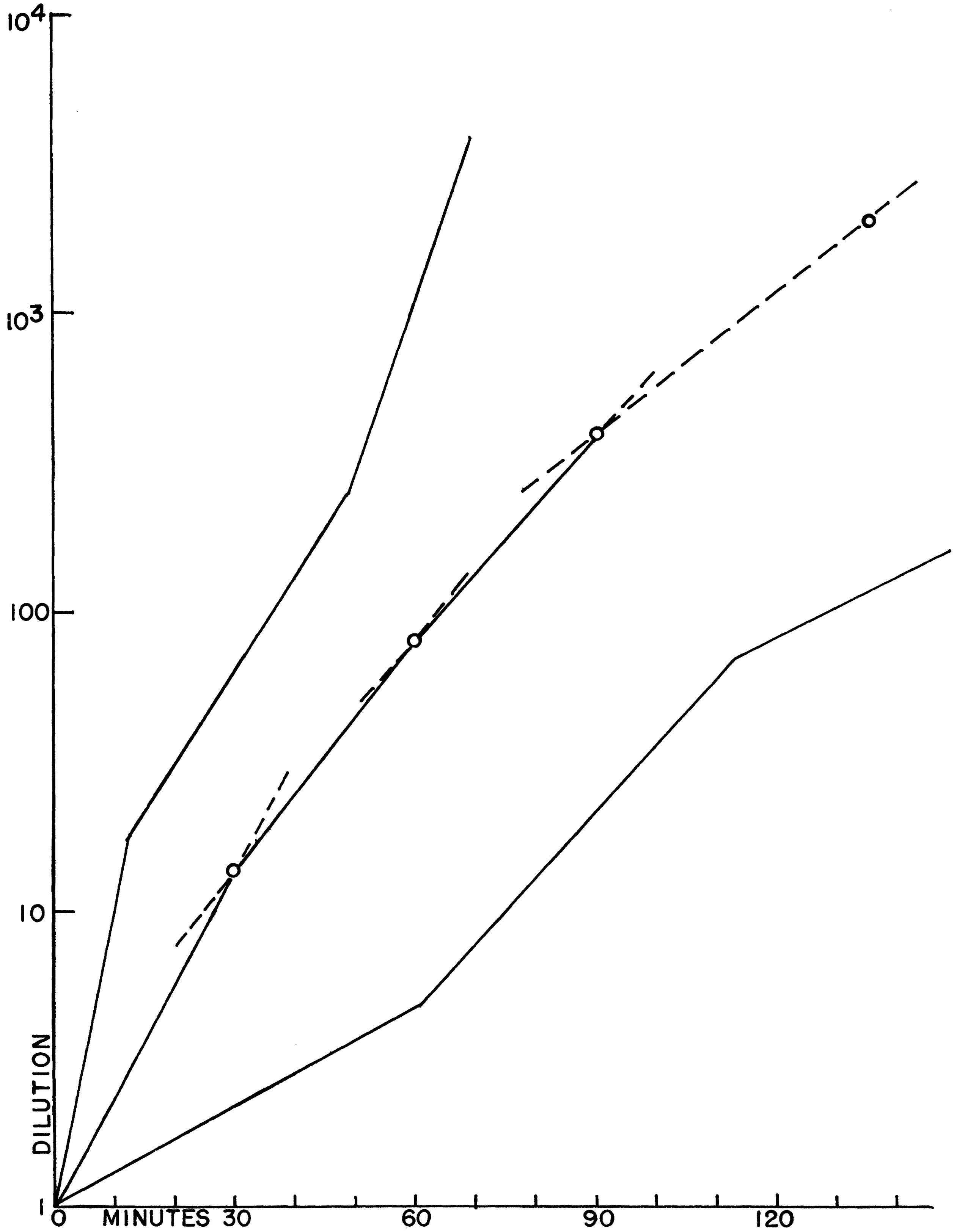

Fig. 8. Envelope of dilution curves, and dilution trend-line.

The net direct results of the dye experiments are that the natural along-shore currents at the reactor site may be expected to provide, under light winds, dilutions of about 14X in the first half hour, about 80X in the first hour, about 400X in the first hour and a half, and something of the order of 1000X at the end of the first two hours. The last of these values is based upon only three observations and must be considered only indicative.

Within the time-limitations of the data, the dilution trend-line appears to have the characteristic of going to a plateau as do those of similar experiments carried out in the ocean.

D. DISCUSSION

The fact that six of the dilution experiments produced true geometric dilutions, while the rest did not, raises the question whether the apparent diminishing dilution rates were real or whether they merely represented failures to find the maximum concentration in the dye patch.

To test this possibility, use was made of the natural boundary condition represented by the volume of Lake Michigan and of the dilution level to be expected when one of our one-gallon dye introductions was dispersed throughout Lake Michigan. Lake Michigan contains about 1.2×10^{15} gallons, and one gallon of dye dispersed through the lake should be diluted to 10^{15} times.

Each of our observed dilutions at one hour was substituted into the dilution equation and the equation solved for $r_{10\ min}$. The mean r_{10} for the first hour was 2.0. The mean wind under which our observations were made was 6 mph, and taking current velocity at 6% of wind speed (see Section V-C) yields a mean current of 0.36 mph which should cover the 5.5 miles to Charlevoix in 15.3 hours or 918 minutes. In this case T/t = T/10 min = 91.8. The dilution equation with these values substituted becomes

$$D(T) = C_o/C(T) = 2^{91.8} = 4.3 \times 10^{27}$$

This value is greatly in excess of the boundary condition imposed by the volume of Lake Michigan, and initial geometric dilutions of the sort shown in Fig. 6 obviously cannot continue indefinitely. The decrease of dilution ratios as observed in the majority of the cases must, then, be expected to represent some kind of real condition.

Since the mechanics of carrying out a dilution run gave our data a natural tendency to clump at about half-hour intervals, these intervals were used in the determination of the several segments of the trend-line about which the observations were distributed. At the end of each half-hour of each experiment the observed dilution factor which applied as a multiplier during the preceding thirty minutes, and the time factor, T/10 min, were substituted into the

dilution equation and the equation solved for the dilution ratio, $r_{10\ min}$. Mean dilution ratios for the intervals 0-30 min, 30-60 min, 60-90 min, 90-120 min, and 120-150 minutes were obtained. These are presented in Table IV.

Extreme scarcity of data in the intervals 90-120 minutes and 120-150 minutes have led to the averaging of the three values involved and to use of the average at 135 minutes. The resulting final segment of the trend-line can be only indicative.

Each mean, along with the proper T/10 min factor, was substituted in the dilution equation and the dilution applicable to each interval computed. These are, with $D_o = 1$,

$$D_{0-30} = 13.8 \qquad D_{30-60} = 5.8 \qquad D_{60-90} = 4.9 \qquad D_{90-135} = 5.3$$

Progressive multiplication then gives the values 14 at 30 minutes, 80 at 60 minutes, 400 (about) at 90 minutes, and about 2000 at 135 minutes which serve as the basic points of the trend-line in Fig. 8.

The above takes no account of the possible effects of the cooling-water discharge from the plant. It is likely that the greatest potential of the cooling-water flow will be in its disruptive effect on the small flattened eddy close inshore at the site. The establishment of an outward flow of 80 cfs where none now exists should lead to improved initial mixing and better initial dilution.

The above considerations do not take account, either, of the decay of the minute amounts of radioactive waste discharged into Lake Michigan.

Lack of long-period dilution data makes it impossible to estimate the probable concentration levels of plant effluent reaching either the Charlevoix or the Penn-Dixie water intake. Current velocities are highest, and travel (dilution) times least, under high winds. Under high winds, however, there is increased turbulence and an increased dilution ratio which at least in part offsets the undesirable effect of shortened dilution time.

The relationship of the first-hour dilution ratio to wind speed at the time of measurement is given in Fig. 9. The $r_{10\ min}$ given in this case is that single ratio that applies during the first hour. Under winds up to 10-12 mph the average first-hour dilution ratio in the alongshore waters between Charlevoix and Petoskey is 2.0. The observed average current speed is 0.34 mph. The relations between dilution ratio and wind speed are given by:

$$r_{10} = 1.48 + 0.081\ W \qquad (9a)$$

$$r_{10} = 1.65 + 0.0066\ W^2 \qquad (9b)$$

TABLE IV

DILUTION RATIOS AT HALF-HOUR INTERVALS

Patch		Minutes				
		0-30	30-60	60-90	90-120	120-150
25 July	I	3.13	1.22	--	--	--
	II	5.29	--	--	--	--
	III	3.74	--	--	--	--
28 July	I	3.00	--	--	--	--
	II	1.37	3.00	1.91	--	--
	III	1.45	1.12	1.66	--	--
29 July	I	2.62	--	--	--	--
	II	3.18	1.47	1.56	--	--
	III	3.06	1.98	--	--	--
1 Aug	I	2.12	1.49	1.07	--	--
	II	--	--	2.19	1.22	1.28
5 Aug	I	1.54	--	--	--	--
	II	1.99	--	--	--	--
	III	1.56	--	--	--	--
6 Aug	I	2.13	1.70	--	--	--
	II	1.84	--	--	--	--
	III	1.97	--	--	--	--
	IV	1.56	--	--	--	--
15 Aug	I	2.66	3.37	--	--	--
	II	2.61	1.30	1.15	--	--
	III	2.22	1.67	--	--	--
	IV	3.39	--	--	--	--
17 Aug	I	1.71	3.04	--	--	--
18 Aug	I	2.57	1.32	--	--	--
	II	2.52	2.00	--	--	--
	III	1.97	2.40	--	--	--
	IV	3.91	1.76	--	--	--
19 Aug	I	1.56	1.38	--	--	--
	II	2.35	1.87	--	--	--
	III	1.64	1.13	--	--	--
	IV	3.34	1.89	--	--	--
22 Aug	I	1.79	--	--	--	--
30 Aug	I	2.42	1.12	2.48	--	--
	II	1.60	1.55	1.61	1.87	--
					avg of 3	
Means		2.42	1.80	1.70	1.46	

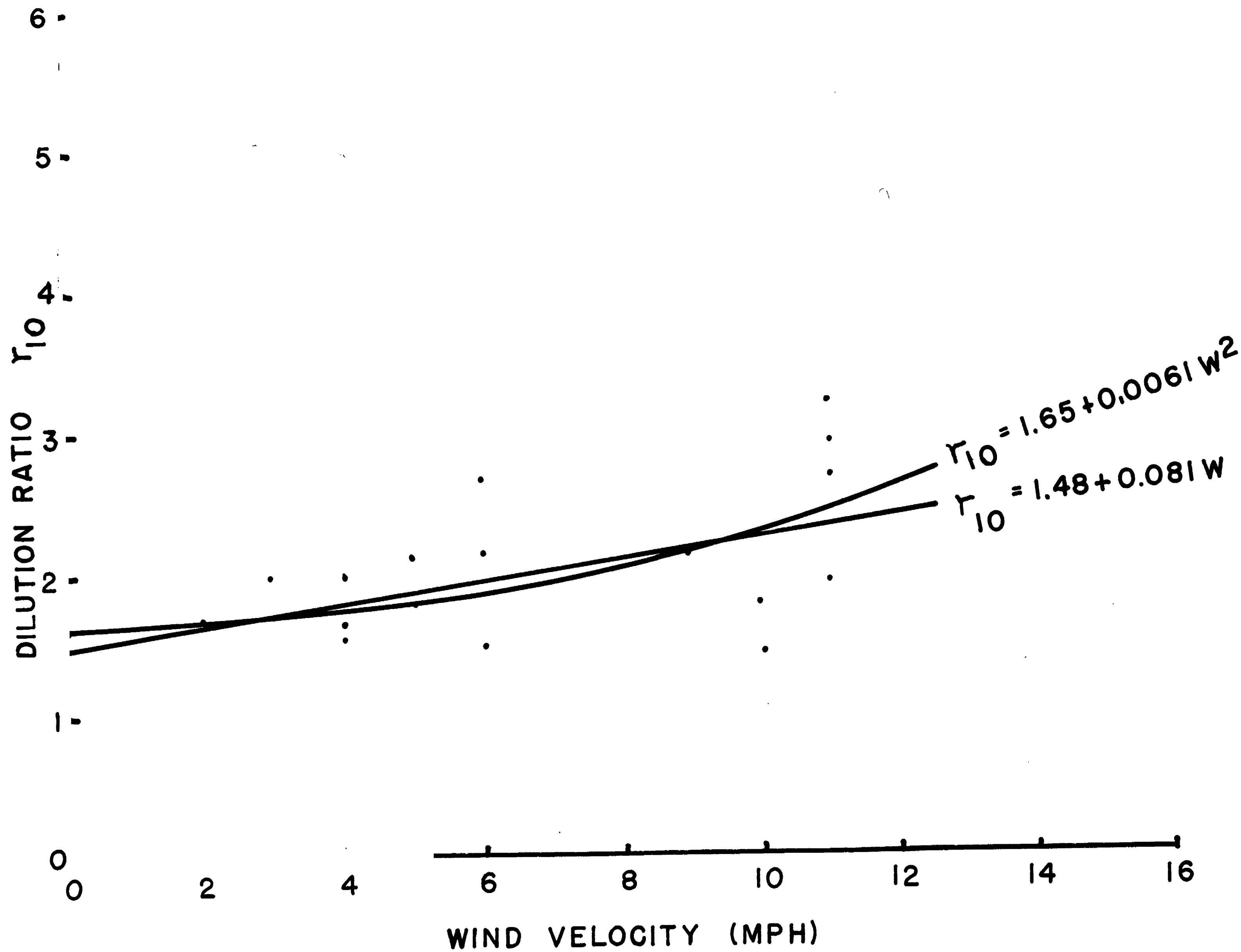

Fig. 9. Relationship of dilution ratio to wind velocity.

Equations (9b) gives a slightly better statistical fit to the data than does (9a) (when using the least-squares criterion), but the value of r_{10} predicted for zero wind speed by (9a) is better than that predicted by (9b). Experience elsewhere has shown that the W^2 relationship is not unlikely.

Equation (9b) can be used to estimate the probable magnitude of the first-hour dilution ratio under various wind speeds. Such estimates for winds up to 15 mph have been made and are given, along with the first-hour dilutions they represent and current-travel times to Charlevoix and Penn-Dixie, in Table V.

TABLE V

FIRST-HOUR DILUTIONS UNDER VARIOUS WIND SPEEDS

			With Current at 6% of Wind Speed	
Wind, mph	First-Hour r_{10} [from Eq. (9b)]	Dilution in First Hour	Hours to Reach Charlevoix (5-1/2 mi)	Hours to Reach Penn-Dixie (9 mi)
1	1.7	24X	91.7	150
5	1.8	34X	18.3	30
10	2.3	148X	9.2	15
15	3.1	880X	6.1	10

Although initial dilutions are low under light winds, current velocities are also low and travel (dilution) times are long. Higher winds produce faster currents and shorter travel times, but they also produce more turbulence and higher initial dilutions. These characteristics inherent in the alongshore currents appear able to provide dilutions of the order of several thousand times in the intervals between Big Rock and Charlevois or Penn-Dixie under the local range of wind velocities.

From present evidence about the nature of the wind-driven circulations in Little Traverse Bay, it appears highly unlikely that recirculation of currents in the bay could bring plant effluents back to the plant's water intake. Under easterly winds the alongshore current which receives the cooling-water discharge is swept out into Lake Michigan. Under westerly winds the plant effluent would travel in the alongshore current to the head of the bay where additional dilution would be received from water that has entered the bay by flowing eastward outside the alongshore current. After sinking and subsurface movement, these waters appear to upwell, and part recirculates while the rest departs the bay as surface current moving to the northwest.

Even under high westerly winds, the alongshore current takes hours to

reach Penn-Dixie. Still more hours would be needed for it to reach the head of the bay, sink, travel down the bay, upwell, and begin recirculation. During this period there would be decay of short-half-life materials.

VII. SUMMARY

Little Traverse Bay is surrounded by relatively high and uneven topography which resulted from the Port Huron and Valders substages of the Wisconsin glaciation. The bathymetry of the bay reflects both the glaciation and an earlier process of irregularity development, probably the solution of salt beds from the underlying Salina rock strata and consequent collapse and recementing of the rocks. Maximum depths more than 300 feet are located in a small area about two miles north of Big Rock Point.

The majority of the submerged area off Big Rock Point is covered by a dense cobble and boulder pavement which overlies red glacial till. In a limited area near Big Rock Point itself limestone bedrock strata are exposed.

The over-all circulation pattern of Little Traverse Bay is incompletely worked out, but it appears to involve (under prevailing winds) a substantial subsurface water movement from the head of the bay to near the bay mouth where a major upwelling in the north central portion of the bay brings water to the surface.

Currents in the vicinity of the reactor site are almost altogether eastward or westward alongshore currents. Shoreline configuration is such that winds from NW through N tend to hold the outflowing current against shore all the way to the Charlevoix water intake. Winds from the SW through W tend to hold the inflowing eastward currents against the shore all the way to the Penn-Dixie intake and Petoskey. Transition phases resulting in reversal of current direction accompany winds from the SE and WNW. A minor elongate eddy appears to be situated, under most winds, in the embayment between Big Rock Point and the highway park; this eddy is driven by the main alongshore current and produces extremely local reversed current directions along the shore in front of the plant site. This eddy is considered unimportant in the dilution properties of the area, and there is doubt that it will survive when the effluent flow from the reactor comes into operation.

Current velocities in the main alongshore currents are about 2% of the mean wind velocity, when winds have been essentially unidirectional on the observation day <u>and</u> the preceding day. They appear to be about 6% of mean observation-day wind velocity when wind of the preceding day has been approximately opposite to that of the observation day. Two equations relating the dilution ratio to wind velocity have been derived.

Thirty-four dye dilution experiments were carried out under light winds when turbulence and dilution could be expected to be minimal. The results indicate that the natural alongshore currents (without the probable beneficial effect of the plant's cooling-water discharge) produce dilutions of 14X in a half hour, about 80X in the first hour, about 400X in the first hour and a half, and something of the order of 1000X in the first two hours. These values were obtained under winds of 0 to 10-12 mph. Higher winds will produce more turbulence and more rapid initial dilution.

The experiments show that for the first hour the dilution process is adequately defined as a simple geometric process, but that after the first hour dilution becomes a decreasing curvilinear function. Similar studies carried out in the ocean have indicated a tendency for dilution to approach a plateau; our experiments appear to show the same tendency, but the order of magnitude of the plateau cannot be determined at present.

There was no observable difference in the diluting capacities of alongshore currents moving into or out from the bay.

It appears highly unlikely that recirculation of currents in Little Traverse Bay will return any plant effluent to the plant water intake.

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